High Subsonic Cavity Flows Forced with Localized Arc Filament Plasma Actuators

Thesis

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By

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Abstract

Engine unstart is a problem in scramjets. The shock train adjusts the incoming flow speed and pressure before it reaches the combustor. If the combustor pressure is too high the shock train is forced out of the scramjet and can potentially cause engine unstart. Cavities can be used to prevent shock movement but at hypersonic speeds it does impose a significant drag penalty. During normal operation the cavity needs to be weakly resonating but when unstart is an impending the cavity needs to be strongly resonating to trap the unstart shock. A previous study has shown localized arc filament plasma actuators can turn a strongly resonating cavity into non-resonating one. Localized arc filament plasma actuators have been used to enhance resonance in a weakly resonating cavity to establish resonance. The actuators were placed across the span of the cavity just upstream of the leading edge. The freestream flow was Mach 0.6 with a Reynolds number based on cavity depth of 2×10^5. Forcing sweeps of the actuators occurred near natural Rossiter modes and the effects on the cavity flow observed.

Quasi-two-dimensional (i.e. the actuators are operating in phase) forcing was found to be best for resonance enhancement. Forcing near the 2nd Rossiter mode and first harmonic of the 2nd Rossiter mode amplified the tonal peak and broadband spectrum to similar sound pressure levels seen in a strongly resonating cavity, the tonal peak was at 145 dB and the broadband spectrum were nearly the same. This study in conjunction with previous work has shown localized arc filament plasma actuators have superior control of cavity flows.

I would like to dedicate this paper to my family

Acknowledgements

First I would like to thank the Air Force Research Laboratory, Ohio Space Grant Consortium, and The Ohio State University for providing funding to make this research possible. I would also like to acknowledge my defense committee Dr. Mo Samimy and Dr. James Gregory for providing me a research opportunity.

Nathan Webb was helpful throughout the year; I learned a tremendous amount from him. I would also like to Mike Crawley and Kevin Yugulis for their guidance throughout the year. All the students in the GDTL made these past two years enjoyable.

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Chapter 1: Introduction

Cavity flows are a ubiquitous problem in both commercial and military aircraft. Examples of cavities in aircraft include weapons bays, optical ports, landing gear bays, and any cutout on the surface of the aircraft. Due to the prevalence of cavities on aircraft, these flows have been researched for several decades [1]. Large pressure fluctuations that occur in the cavity are extensively studied and controlled. Negative effects of these pressure fluctuations include high drag and high noise levels. The impingement of the flow on the aft wall fatigues the structure and can lead to failure [1]. With the advent of lightweight, “smart” bombs, the shear layer has the potential to affect the trajectory of the weapon; sometimes even causing the munitions to deflect back into the weapons bay [1].

A relatively new, lesser-known use for a cavity is as a shock trap in the isolator section of a scramjet [2]. The shock train in a scramjet isolator adjusts the flow to the combustor pressure; however, if the fuel equivalence ratio is too large, the combustion-induced high pressure can force the shock train towards the engine inlet. If the shock train coalesces and becomes strong enough at the inlet, the flow will not be supersonic in the combustor, resulting engine unstart. The rapid area change caused by the cavity accelerates the flow and could arrest a moving shock train.

At low speeds the combustor can more easily choke the flow; therefore operation of the engine is safer at higher speeds. Since the engine is safer at higher speeds the cavity needs to be weakly resonating during normal operation otherwise the cavity is imposing a massive drag penalty without any benefits. When a shock is moving towards the inlet, scramjet resonance would need to be established immediately and letting the cavity naturally reestablish the feedback loop could take too long. A previous study by Yugulis [3] has shown Localized Arc Filament Plasma Actuators, LAFPAs henceforth, are capable of disrupting the natural feedback loop and creating a weakly resonating cavity. LAFPAs are a form of plasma actuators developed at the Gas Dynamics and Turbulence Laboratory at The Ohio State University for control of high-speed flows. LAFPAs were developed to force the flow by rapidly heating the flow to manipulate naturally occurring instabilities in the flow resulting significant changes in the flow with a low power input.

To author's knowledge there have not yet been any studies attempting to enhance resonance in a cavity. This research project uses the same plasma actuators as Yugulis to take a non-resonating cavity and convert it to a high drag, resonating cavity, with the potential ability to arrest an upstream travelling unstart shock. This proof-of-concept research builds upon the work done by Yugulis.

Chapter 2: Background

A. Fundamental Physics of Cavity Flows

Cavities are traditionally categorized as open, transitional, or closed which depends on the length to depth ratio (L/D). Figure 1 shows a schematic of both an open and closed cavity. Open cavities typically have L/D typically between 4 and 7. The open cavity is sometimes referred to as shear layer mode because the shear layer flow phenomenon dominates this type of cavity. In a shear layer dominated cavity the main feedback mechanism is acoustic. As L/D increases from 7 to 10 the cavity becomes transitional. When L/D is 10 or greater the cavity is closed; this is also known as wake mode. In a closed cavity, the shear layer reattaches to the floor of the cavity and exhibits similar behavior to the wake behind a cylinder in cross flow, commonly known as vortex shedding. Due to the absolute instability the feedback mechanism for wake mode is hydrodynamic [4]. This work examines a closed cavity and will only be discussed for the rest of this paper.

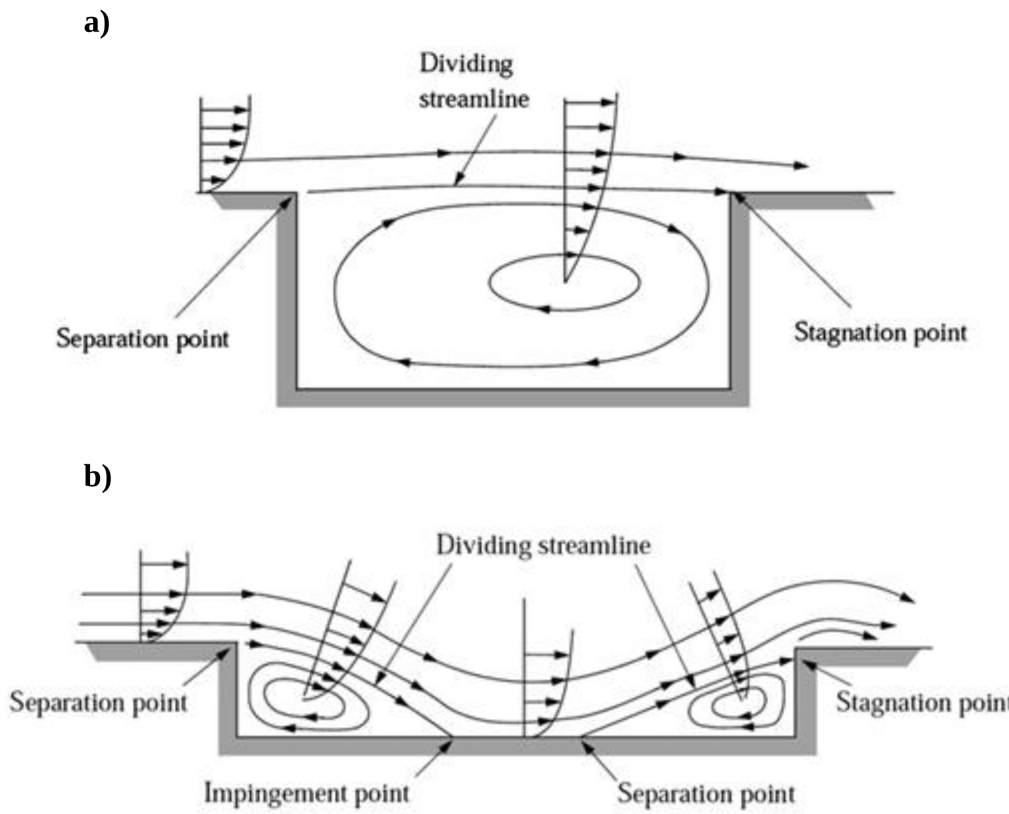


Figure 1: Open (a) and closed (b) cavities with stream lines (Courtesy of ref. [5])

A shear layer dominated cavity is dominated by large unsteady pressure fluctuations. In a cavity flow, the pressure spectra depend on several factors, including freestream Mach number, boundary layer thickness, and momentum thickness. A schematic of an open cavity flow is presented in Figure 2. The incoming flow passes the leading edge and the boundary layer and momentum thickness form a shear layer. The stability of the shear layer depends on its thickness; the thicker the shear layer the less severe the velocity gradient and therefore the less sensitive the shear layer is to disturbances. Disturbances in the initial shear layer roll up into large-scale structures through the Kelvin-Helmholtz instability and impinge on the aft wall of the cavity that generates an acoustic wave. If the freestream velocity is subsonic, the acoustic waves radiate in all directions while in a supersonic flow the acoustic wave travels upstream within the cavity. The acoustic wave travels upstream and seeds the flow at the leading edge. The shear layer selectively amplifies frequencies of the perturbation, developing into a vortex; thereby completing the feedback loop and establishing resonance. This feedback loop generates vortices which large pressure fluctuations that dominate a strongly resonating cavity.

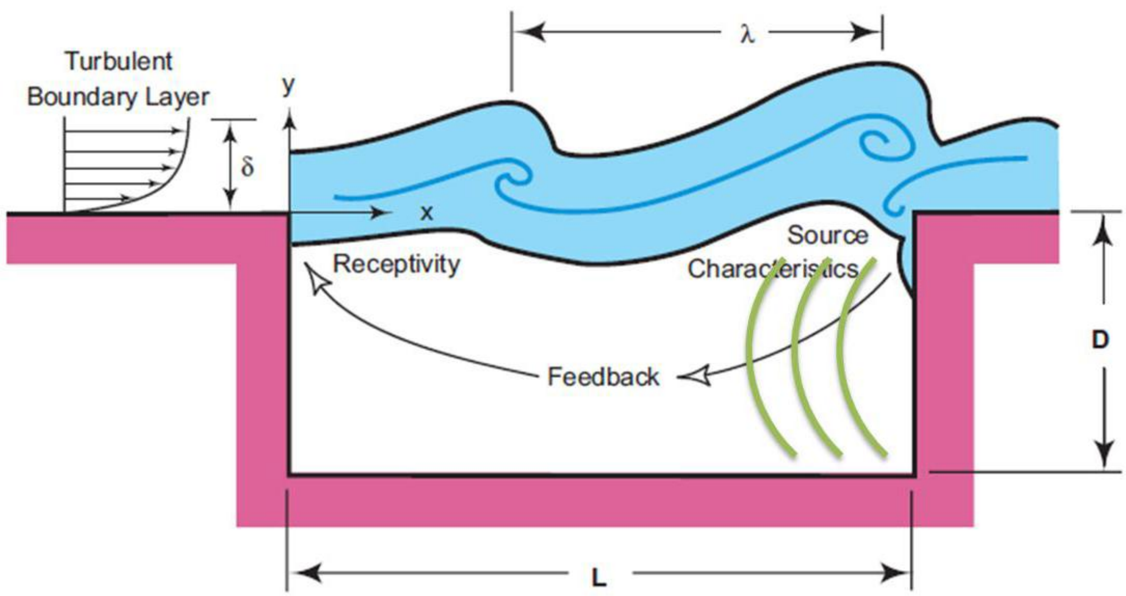


Figure 2: Schematic of an open cavity with important parameters (Courtesy of ref. [1])

Rossiter [6] was the first to develop a semi-empirical formula describing cavity resonance. For this reason the natural frequencies are commonly referred to as Rossiter modes. While this was a significant step, Heller [7] refined the equation, as seen in Equation 1, to the equation commonly used today:

$$St_n = \frac{f_n L}{U} = \frac{n-\varepsilon}{M\left\{1+\left[\frac{\gamma-1}{2}\right]M^2\right\}^{-1/2}+\frac{1}{\beta}} \tag{1}$$

The Strouhal number is related to the freestream Mach number, the ratio of the convective velocity of the vortices to the free stream velocity, and an empirical constant, ε, determined to be 0.25 and the ratio between convective velocity, β, of vortices to the freestream velocity was found to be between 0.57 and 0.66 [6]. The constant ε is generally accepted but β has been thoroughly researched and its value changes depending upon how it is measured. Although Malone et al. [8] have studied a more accurate means of determining these values and provided new equations for both ε and β. Hirahara et al. [9], Murray et al. [10], and Ashchroft et al. [11], have experimentally determined beta to be 0.57 for subsonic and transonic flows.

Rossiter modes are typically related to the longitudinal mode of the cavity [12]. However, Debiasi et al. [13] saw an exception where the Rossiter modes aligned with the transverse modes. This difference can attributed to not having acoustic absorbing material on the ceiling of the test section. Acoustic absorbing material is typically installed on the ceiling to simulate being in open air.

While the Rossiter equation states that there could be a theoretically infinite number of modes at which the cavity can resonate, previous studies have shown the dominant Rossiter mode is typically the 2^{nd} or 3^{rd} mode [4].

Under certain flow conditions, a cavity experiences a natural phenomenon termed mode switching. Mode switching is when a cavity rapidly vacillates between two or more Rossiter modes. When this occurs the mean energy of the shear layer is divided between two or more modes and the feedback loop is diminished. This phenomenon is well documented. Figure 3 displays measurement of a cavity which shows evidence of mode switching and is the baseline case of a weakly resonating cavity for this project. Notice how the Sound Pressure Level (SPL) has strong peaks relative to the broadband around 2500 Hz, 3500 Hz, and 5000 Hz. Usually when mode switching occurs the tonal peaks are weaker than for a cavity which does not experience mode switching. Mode switching was beneficial when the LAFPAs were trying to attenuate these tones.

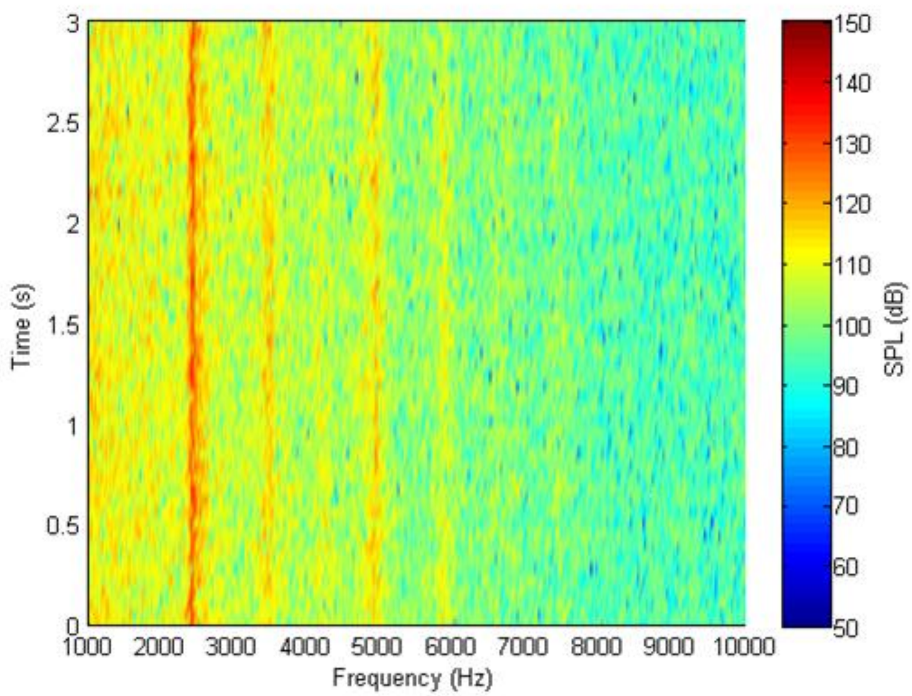


Figure 3: Weakly resonating cavity with mode splitting between 2nd, 3rd, and 4th Rossiter modes

B. Engine Unstart in Scramjets

Engine unstart has been extensively researched because of its potential detrimental effects to successful scramjet operation. Figure 4 shows a schematic of a scramjet. A scramjet generates a series of oblique shocks, called a shock train, which forms at the inlet of the engine and continues through the isolator. The shock train slows and compresses the flow down to prepare it for combustion. However; it is still supersonic when it reaches the combustor. The fuel ignites and exhausts out the rear of the engine. If the equivalence ratio becomes too great, the heat release will choke the flow in the combustor. The back pressure in the combustor and the unstart shock will then force the shock train out of the isolator section and potentially cause engine unstart.

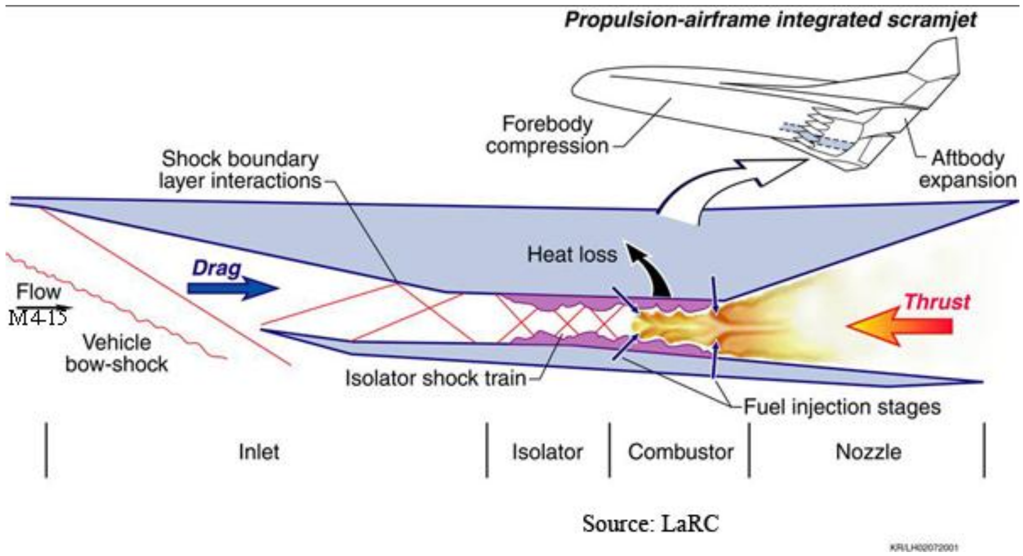


Figure 4: Schematic of scramjet engine (Courtesy Ref.[14])

Preventing unstart has been studied in the past. Typical recommendations include extending the isolator section; however, this makes the engine heavier and reduces performance. There have been attempts to use LAFPAs in the inlet to prevent boundary layer separation [15]. Valdivia et al. [16] used a combination of Wheeler Doublets (WDs) and Vortex Generation Jets (VGJs) to prevent the shock train from moving but were limited by their controller. This work investigates arresting the shock train by simulating a cavity in the isolator section of the engine except the flow will be subsonic.

Currently, scramjets, such as the X43 and X51, operate at hypersonic speeds, Mach 5 to Mach 10. In this flow regime the cavity would impose a significant drag penalty. In order to mitigate the drag penalty the cavity would need to be non-resonating during normal operation. Then, when the shock train is threatening to move out of the engine, the cavity would need to be altered to become highly resonating. Yugulis [3] demonstrated that LAFPAs were able disrupt the feedback loop in a resonating cavity, thereby reducing the drag. That study simulated an internal flow such as that found in a scramjet isolator. In this work forcing near the natural frequencies of the cavity enhanced resonance to demonstrate the LAFPAs have full control of a cavity flow.

C. Flow Control Techniques

The detrimental effects of cavity flows prompted studies to attempt to mitigate the effects. Gharib and Roshko [17] demonstrated that control was able to reduce drag by up to 250%. Current control techniques can be categorized as either passive or active. Passive flow control does not input energy into the flow and is usually takes the form of a geometric modification. Passive control has many limitations; these techniques are permanent, usually impose a drag penalty, and are typically ineffective outside of their design conditions. Flow over the aircraft is constantly changing so having control techniques that are not adaptable to different flow conditions is not an attractive option. Active control inputs energy into the flow through a variety of means, including electrical, thermal, or acoustic energy. Active control is able to adapt to the flow and is a more attractive option, even though it is more complicated than passive control. This paper will not provide a comprehensive review of studies but will refer the reader to Cattafesta et al. and Lawson and Barakos for overviews of past studies. [1, 5].

1. Passive Control

As previously stated, most passive control techniques are geometric modifications. Some examples are fences, ramps and spoilers, and hinged flaps [1]. Fences thicken the boundary layer, which increases the stability of the shear layer. The velocity gradient is less severe, and the shear layer becomes more resistant to seeding by the acoustic wave. This lessens the strength of the eventual roll up into large scale structures. Previous researchers have noted that the boundary layer thickness should be greater than 7% of the length of the cavity for sufficient attenuation [1]. Flaps and ramps and spoilers operate by affecting the trajectory of the shear layer so the impingement of the flow on the aft wall is not as severe. These actuators are usually able to force at a low frequency but a high frequency passive controller is placing a cylinder at the leading edge of the cavity. This technique forces the flow at high frequency and is able to force the flow at the frequency of the vortex shedding. The importance of high frequency forcing will be discussed in the active control section. These techniques usually cannot respond rapidly to varying flow conditions.

2. Active Control

Active control is used because it can rapidly respond to varying flow conditions. Numerous cavity studies have been performed with active control techniques across several flow conditions. Active control can be further reduced to open loop and closed loop feedback control; the former does not automatically adapt to flow conditions while the latter is able to adjust to flow conditions without an external input. Several controllers for implementation of feedback control have been designed and thoroughly studied. Debiasi et al. [13] used a logic based controller to adjust the forcing of a titanium diaphragm to achieve maximum tonal attenuation. While tonal peaks were reduced, the broadband spectrum was largely unaffected. Microjets and resonance tubes were effective in peak tone reduction as well as broadband reduction [1]. While all these forms were effective in some form of attenuation; to the author's knowledge none have ever been used for peak tone enhancement and broadband spectra increases. The actuators used in this experiment are active and have are used to provide open loop control.

D. LAFPAs

The Gas Dynamics and Turbulence Laboratory at the Ohio State University uses a form of active actuators called LAFPAs. A LAFPA consists of electrodes. One electrode is connected to a circuit to make the charge high voltage and low current and the other is grounded. When the voltage breakdown of the air between the electrodes is reached a plasma arc forms. This plasma arc operates by rapid localized Joule heating which causes a thermal perturbation in the flow that, in a cavity flow, rolls up into a vortex via the Kelvin Helmholtz instability. All five actuators were placed evenly across the span of the cavity in a groove. The groove is to prevent the flow from blowing off the plasma; this allows the actuators to achieve a quasi-steady operation. Samimy et al. [18-20] studied the control authority of the LAFPAs over both supersonic and subsonic jets [18-20]. A picture of the cavity and the LAFPAs operating can be seen in Figure 5. Note how the second actuator's arc is not as large as the others; this is because the frequency but not the magnitude of the actuators can be controlled. The magnitude of the pulse depends on many factors a couple of which are: degradation of the electrode and air surrounding the electrode.

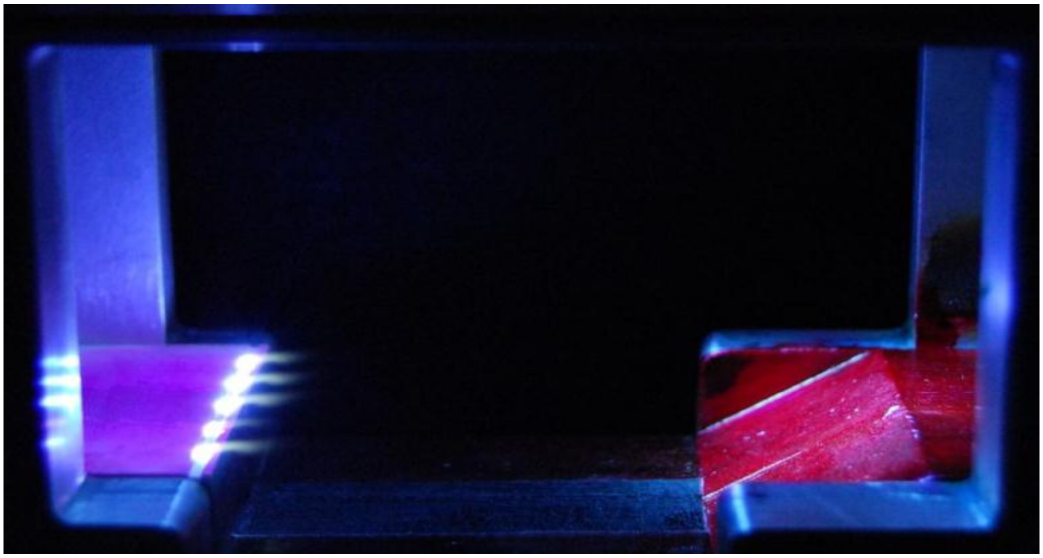


Figure 5: Plasma actuators operating in cavity flow

Yugulis [3] used LAFPAs to reduce both the broadband spectra and tonal peaks [3]. The LAFPAs were effective in disrupting the resonance, especially when operated at high frequencies in a three–dimensional mode by introducing jitter into the flow. PIV data was taken for several forcing cases to determine the effect of the LAFPAs. The swirl strength observed in the 3-D forcing cases was significantly lower than similar quasi-2-D forcing frequencies, leading to a further reduction in the tonal peaks and broadband. At these conditions the LAFPAs generated several vortices which competed for the mean flow energy. This resulted in 25 dB peak tone reductions and 5 dB broadband spectra decreases from the baseline cases.

The effects of the actuators are shown Figure 6. Note the approximately 3 dB drop between the quasi-2-D forcing and 3-D forcing. This demonstrates that the actuators introduce more jitter in the shear layer when the forcing is three-dimensional. This result was also noticed in forcing cases for a weakly resonating cavity and will be further discussed in the results section.

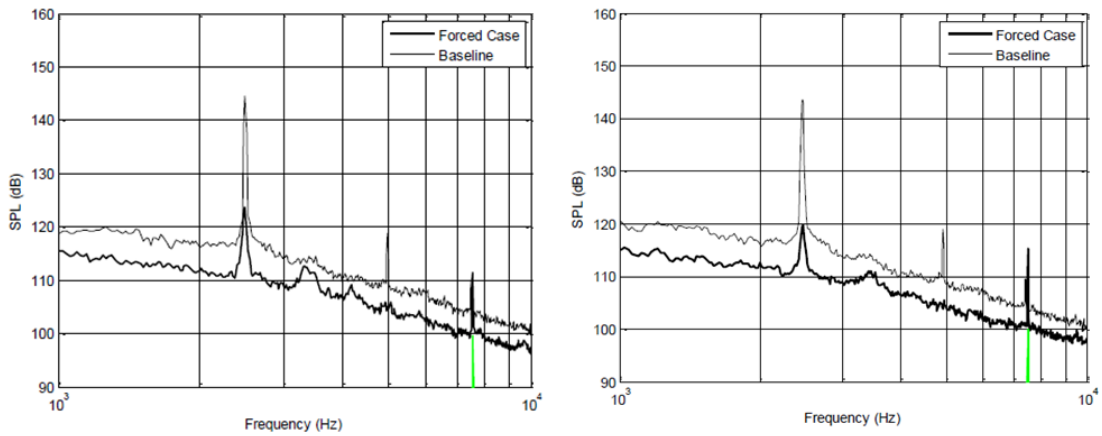


Figure 6: Quasi-2-D and 3-D forcing at 7550 Hz in a strongly resonating cavity

Chapter 3: Experimental Procedure and Facilities

A. Experimental Facility

The current facility is a blow-down type wind tunnel. The air is compressed, dried, filtered, and stored up to 15 MPa in two storage tanks. The tunnel is capable of running continuously with two five-stage reciprocating compressors. The stagnation pressure can be held constant within ±335 Pa at Mach 0.6 flow with a Reynolds number of $2x10^5$ based on cavity depth. The air passes through a large stagnation chamber and a series of various screens to reduce turbulence in the flow. After the stagnation chamber, the flow goes through a smoothly contoured subsonic nozzle and into a 50.8 mm by 50.8 mm test section. The angle of the test section ceiling is fully adjustable. The aft wall of the cavity is slanted at 30° above horizontal to reduce the strength of the feedback loop. The length of the cavity is 61.7 mm, mid-plane of the slanted wall, 12.7 mm deep, and 50.8 mm wide, which spans the width of the test section. Therefore the geometric ratios for this cavity are L/D of 4.86 and W/D is 4. The cavity is able to be treated as two dimensional so the origin of the cavity is centerline of the leading edge of the cavity [3]. A CAD model of the test section and nozzle are presented in Figure 7.

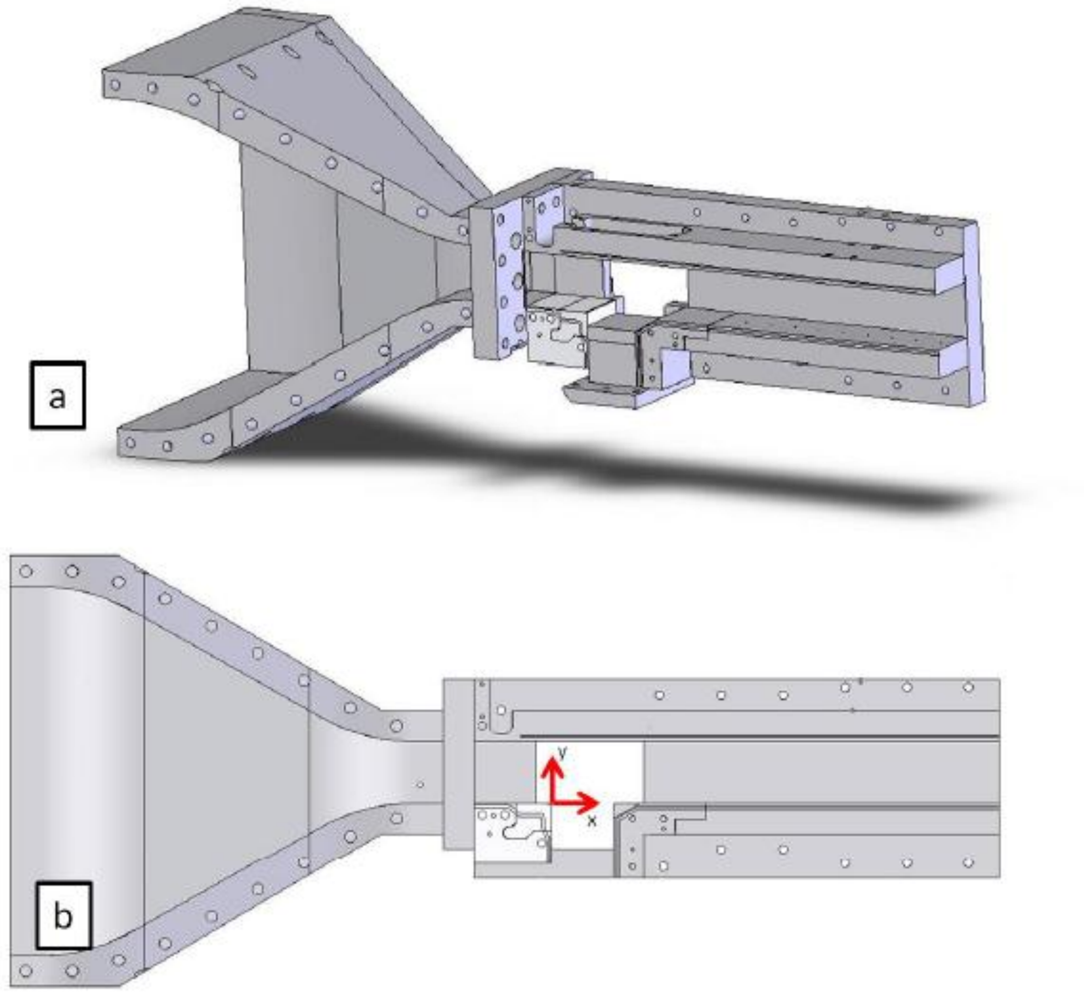


Figure 7: CAD model of cavity and test section

B. Ceiling Height Determination

As previously stated the ceiling is fully adjustable. The ceiling angle is generally adjusted to compensate for the growth of the boundary layer; however, for this research the ceiling height is adjusted to make the cavity weakly resonating. The ceiling height is adjusted by a knob about 11.5” from the leading edge of the cavity. The hinge is 13” from where ceiling height measurements were taken. A previous study has extensively described the experimental facilities; if further information about the experimental setup and facilities is desired refer to Yugulis [3]. In this research the ceiling height was adjusted 0, 2, 3, 4, 5, and 6 mm above the normal test section height of 50.8 mm. Static pressure readings were taken at 15 ports that spanned 8.5D upstream to 26D downstream from the leading edge of the cavity. Static pressures were measured and normalized by the ambient pressure as seen in Figure 8. Table 1 presents normalized pressure data which was used to determine three ceilings height that would undergo further investigation.

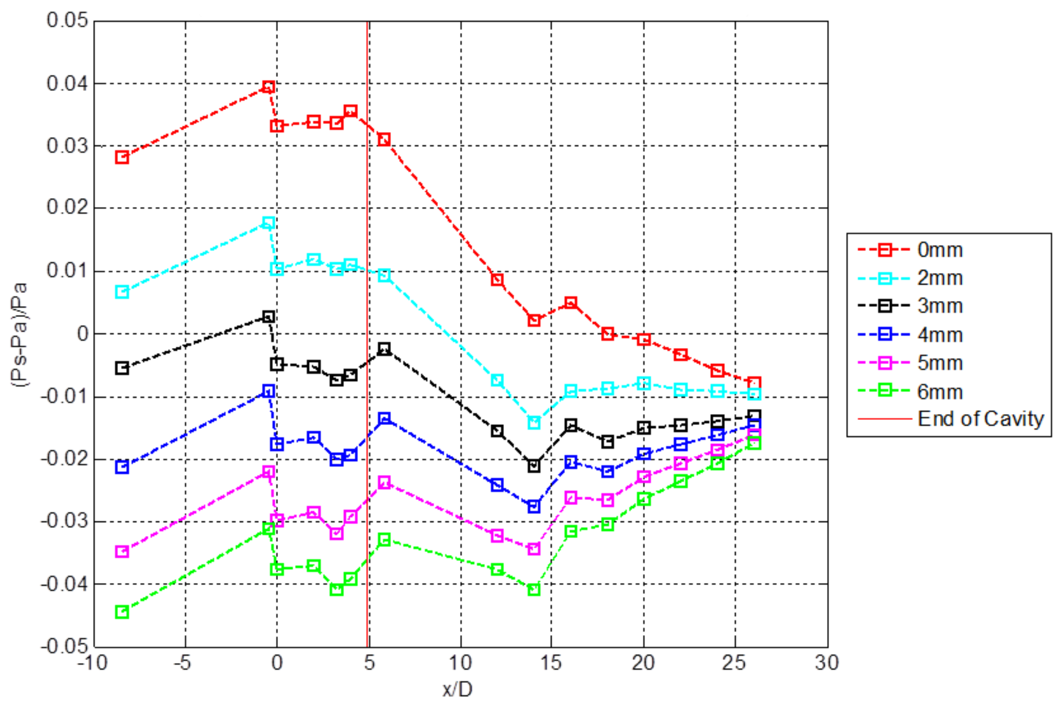


Figure 8: Gauge static pressure ratios for various ceiling heights

Table 1: Maximum, minimum, average, and standard deviation of gauge static pressure ratios for various ceiling heights

Ceiling Height Adjustments	Maximum Value	Minimum Value	Average	Standard Deviation
0 mm	0.039	-0.0078	0.016	0.018
2 mm	0.018	-0.014	0.0017	0.011
3 mm	0.0027	-0.021	-0.009	0.007
4 mm	-0.0093	-0.028	-0.019	0.005
5 mm	-0.016	-0.035	-0.025	0.006
6 mm	-0.017	-0.044	-0.031	0.008

Three ceiling heights with the lowest standard deviation were chosen because they had the most consistent pressure throughout the test section. Their baseline SPL was recorded for in a Mach 0.6 flow, shown in Figure 9: Sound pressure level for 3 most consistent ceiling heights. The dominant peak in the highly resonating cavity was around 2400 Hz. As the ceiling height was adjusted, the peak frequency remained consistent. The only changes in frequency were due to the change in temperature in the stagnation chamber. A maximum peak of 142 dB at 2472 Hz was recorded for the 3 mm ceiling height configuration. The 4 mm, 0.75°, ceiling height adjustment had a maximum peak of 126 dB at 2472 Hz. The 5 mm ceiling adjustment had a peak of 123 dB at 2454 Hz. The 16 dB drop from 3 to 4 mm signified that the cavity drag was sufficiently reduced so as to be useful for the proposed application, therefore, this configuration was used for the remainder of this work. Interestingly the peak near the 4th Rossiter mode increases as the ceiling height increases, and even becomes stronger than the 2nd Rossiter Mode when the ceiling height is 5 mm. This trend was not studied further but requires further investigation. The 4 mm ceiling height adjustment equates to a ceiling angle of 0.75°.

While the isolator section of a scramjet is straight this experiment is to prove the capabilities of the LAFPAs in establishing resonance in a cavity; therefore, the ceiling height is adjusted to attain a weakly resonating cavity.

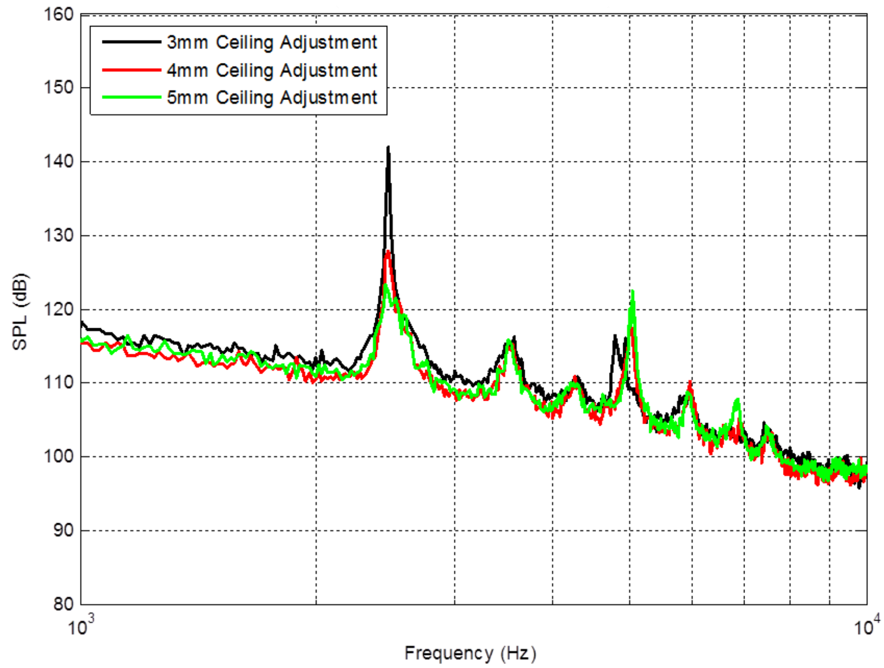


Figure 9: Sound pressure level for 3 most consistent ceiling heights

C. Data Acquisition

Three Kulite pressure transducers, model XTL-190-25A, were placed along the centerline of the cavity floor at 12.7, 25.4, 38.1 mm from the leading edge. These locations normalized by cavity depth are 1, 2, and 3, respectively. Yugulis [3] calibrated the Kulites using a water manometer and found the transducers to have a linear response. Another Kulite is placed outside the facility for EMI detection. As will be discussed later the Kulite recordings were shifted to determine the actuator frequency but the channel for this Kulite on the signal conditioner went bad and was ignored.

The pressure measurements were collected at a sampling frequency of 75 kHz for 3 seconds resulting in a total of 225,000 data points for each test case. Pressure transducer signals were amplified and low-pass filtered with a cutoff frequency of 25 kHz, and collected using a National Instruments data acquisition card PCI-6143.

Quasi-2-D and 3-D forcing sweeps occurred at predetermined frequencies, 2500, 3500, 5000, 6000, and 7500 Hz, which are near theoretical Rossiter modes 2, 3, 4, 5, and 6. Forcing occurred in 50 Hz intervals for ±400 Hz of the before mentioned frequencies as well as a sweep from 1-16 kHz in 1 kHz increments. Quasi-2-D forcing is when all 5 LAFPAs operate in phase and 3-D forcing is when the actuators operate out of phase as seen Figure 10. The placement of the Kulites and LAFPAs in the test section are shown in Figure 11.

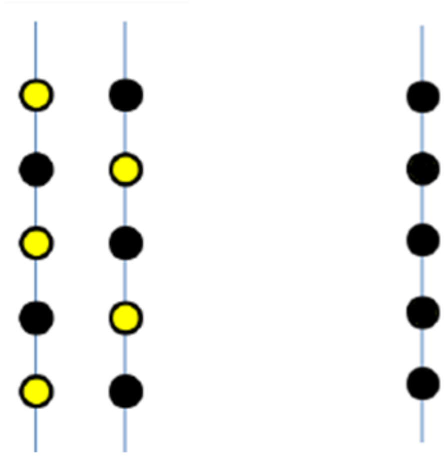


Figure 10: Left figure is the 3-D forcing sequence and the right is the quasi-2-D forcing sequence. Black indicates when the actuators are on.

To determine the effectiveness of the actuators, cavity SPL spectra were calculated. The reference pressure for the SPL in this work is 20 μPa. The spectra were calculated using a bin size of 4096 points and a Hann windowing function. The bin size yields a frequency resolution of 19 Hz. The amount of data collected allowed for the spectrum to be generated from an average of 54 individual spectra. Tonal amplification was determined by the difference in the peaks at either the 2nd or 3rd Rossiter mode. Trapezoidal integration is used to approximate the broadband spectra amplification. For further information on data acquisition please refer to Section 4.1 in Yugulis [3].

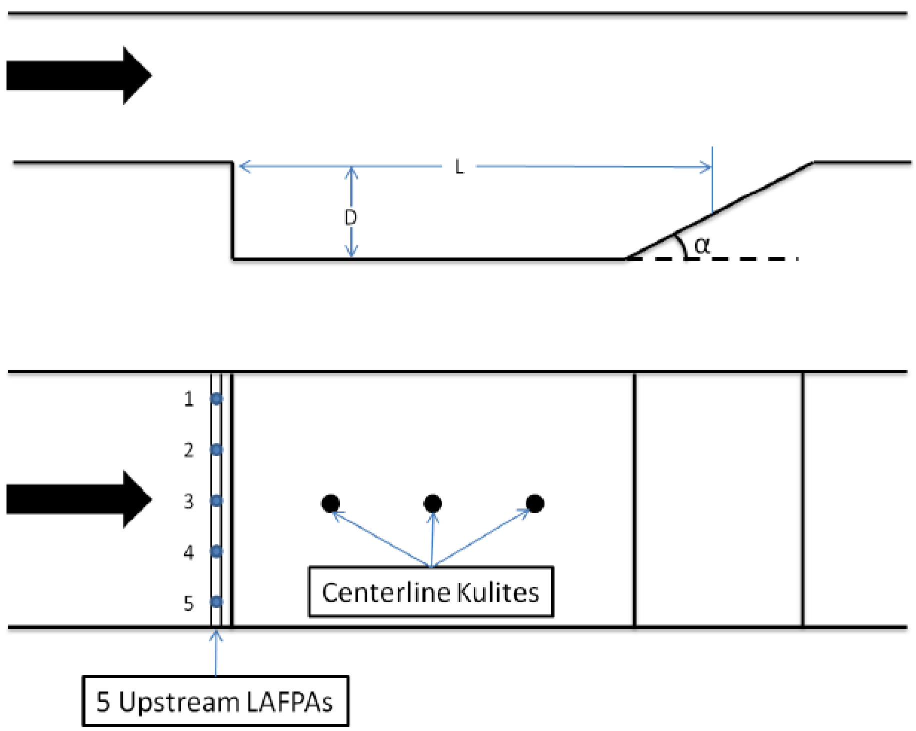


Figure 11: Actuator and Kulite locations in the test section

The reduction in stagnation temperature over the duration of testing caused the frequency of the Rossiter modes to decrease. Please refer to **Error! Reference source not found.** for more detailed information regarding this frequency shift due to temperature.

Table 2: Rossiter mode frequencies and temperature dependence

Rossiter Mode	**Frequency (Hz) – 22 ^{0}C (Starting Temperature)**	**Frequency (Hz)-2^{0}C (Steady-State Temperature)**	**Drop in Frequency over Duration of Test (Hz)**
2nd	2510	2423	87
3rd	3944	3808	136
4th	5379	5193	186
5th	6813	6578	235
6th	8247	7963	284

To counteract this shifting, baseline cases were taken for every two forcing frequencies. The forcing cases are subsequently compared to the nearest baseline case. Since the frequencies of the Rossiter modes decrease significantly as temperature decreases, several tests were run in succession until at the same forcing frequency until the effects of the actuators are similar to those seen operating when the stagnation temperature is at steady state. At 283 K to 275 K, which is the steady state temperature of the stagnation chamber, the effects of forcing are similar to each other. If the stagnation temperature was above 283 K the effects of forcing were reduced due to the shifted frequency of the Rossiter mode. As temperature increases beyond 283 K the effects of actuation were further reduced.

Chapter 4: Data Analysis

A. Baseline of a Weakly Resonating Cavity Flow

The baseline SPL of the weakly resonating cavity was found to have several peaks; however, the second Rossiter mode was still dominant. This SPL is shown in Figure 12. This peak was still near the intersection of the longitudinal mode, referring to Figure 13 and the 2nd Rossiter mode, which is consistent with several previous studies [3, 8]. The peaks shown in Table 3: Peak frequencies and magnitudes for baseline case in a weakly resonating cavity are from the downstream Kulite It has been determined that the strongest pressure fluctuations occur near the aft wall due to the vortices developing and growing [8]. Thus, since it is the region of greatest fluctuation, the downstream Kulite will be used for the rest of this paper. This region also contains the greatest level of recirculation [4, 5]. In Figure 12 the reader will notice the control Kulite is recording a pressure. Even though it was shifted the peaks should not exist; during forcing cases sometimes the control Kulite didn't even record a signal. Therefore, the channel was determined to be bad and ignored.

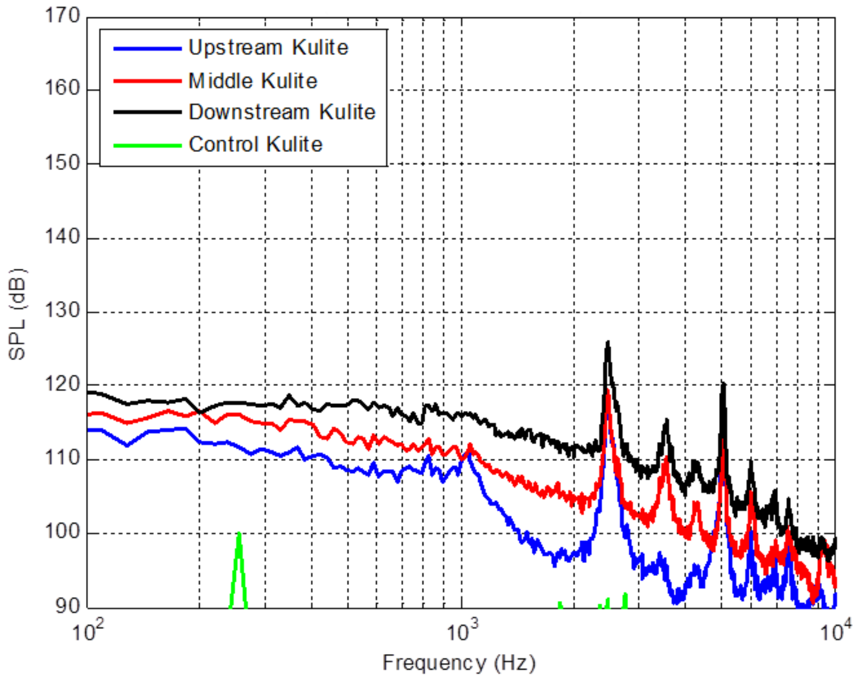


Figure 12: Baseline SPL data for a weakly resonating cavity with all 4 Kulites

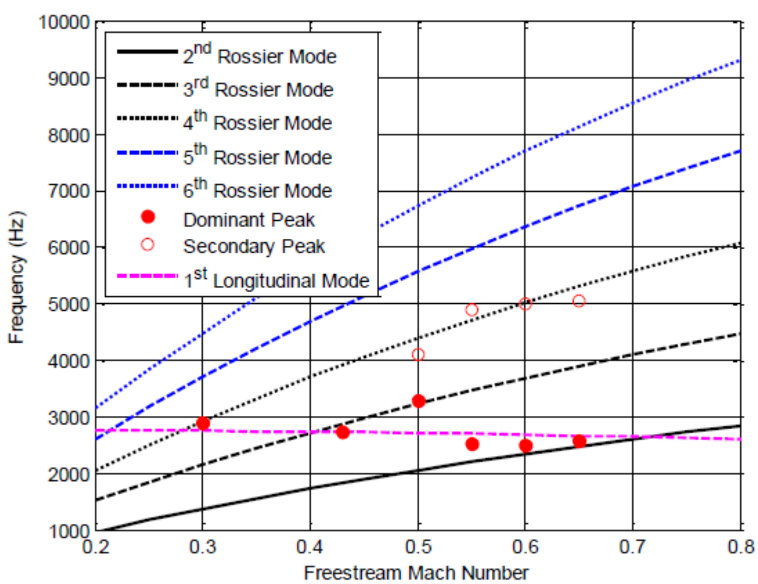


Figure 13: Primary and secondary peaks for cavity with a slanted aft wall (Courtesy of ref. [3])

Table 3: Peak frequencies and magnitudes for baseline case in a weakly resonating cavity

Peak Frequency [Hz]	Peak Pressure Level [dB]
2472 Hz	125.9 dB
3571 Hz	115.3 dB
5035 Hz	120.2 dB
5969 Hz	109.9 dB

SPL from the downstream Kulite is compared with the spectrogram for the baseline case. The SPL graph shows several peaks but the 2nd Rossiter mode is still the dominant, about 15 dB above the broadband. Additionally, its dominance appears to be relatively constant in time and lasts throughout the test. The peak at the 3rd Rossiter mode is approximately 7 dB above the broadband but is sporadic throughout the test. The 4th Rossiter mode is 8 dB above the broadband and its presence is more consistent than the 3rd Rossiter mode but not as consistent as the 2nd Rossiter mode. The spectrogram in Figure 14 when transitioning from the strongly to weakly resonating cavity, the peak at the 4th Rossiter mode and several other peaks, 3rd and 5th most notably, form at the expense of the 2nd Rossiter mode.

Compared to the strongly resonating cavity (displayed in Figure 15) the broadband is reduced by about 5 dB, and the tonal peak is about 20 dB lower. Raising the ceiling height has significantly reduced the impingement strength of the shear layer on the aft wall of the cavity. This in turn has led to a reduction in the strength of the upstream propagating acoustic wave and ultimately disrupted the feedback loop.

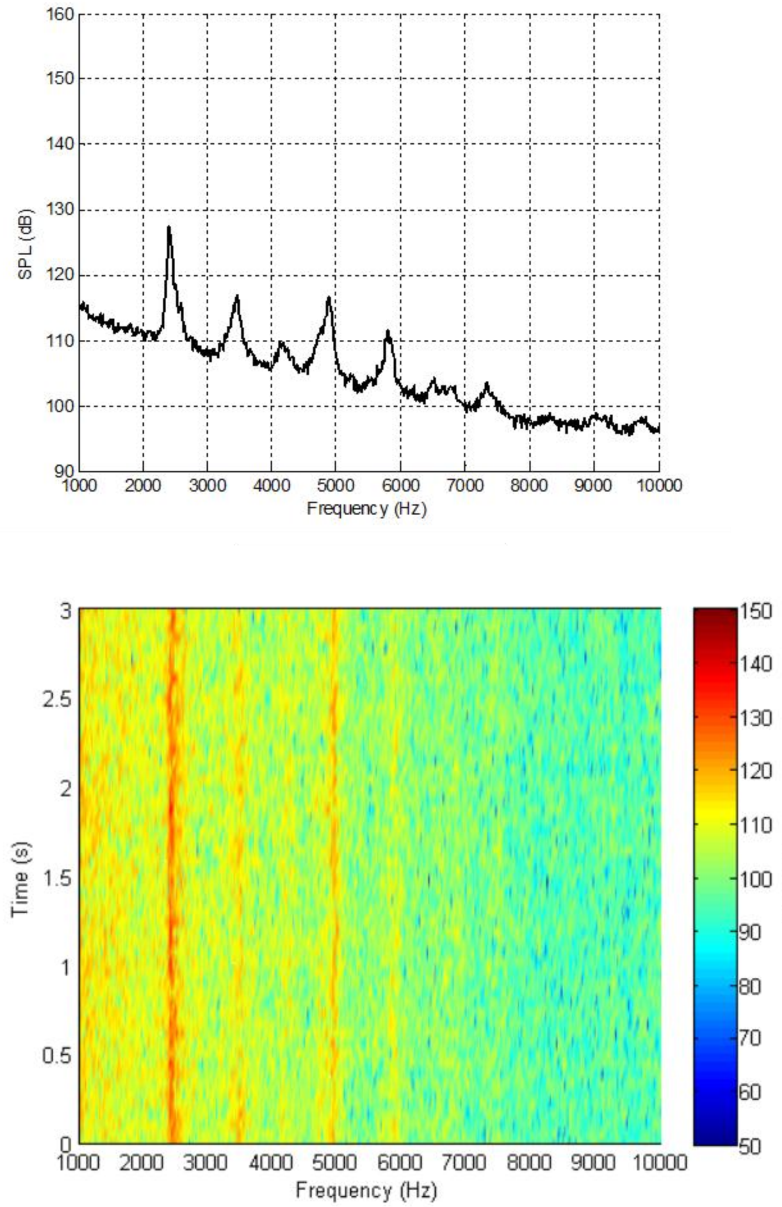


Figure 14: SPL and spectrogram for baseline case in a weakly resonating cavity

Figure 15 provides the SPL graph and spectrogram of a strongly resonating cavity. The most successful forcing cases will be compared to these values to determine the effectiveness of the actuators at enhancing resonance. The strongest peak is at the 2nd

Rossiter mode, 2400 Hz, and its magnitude is 145 dB. There are two secondary peaks, both of which are harmonics of the 2nd Rossiter mode.

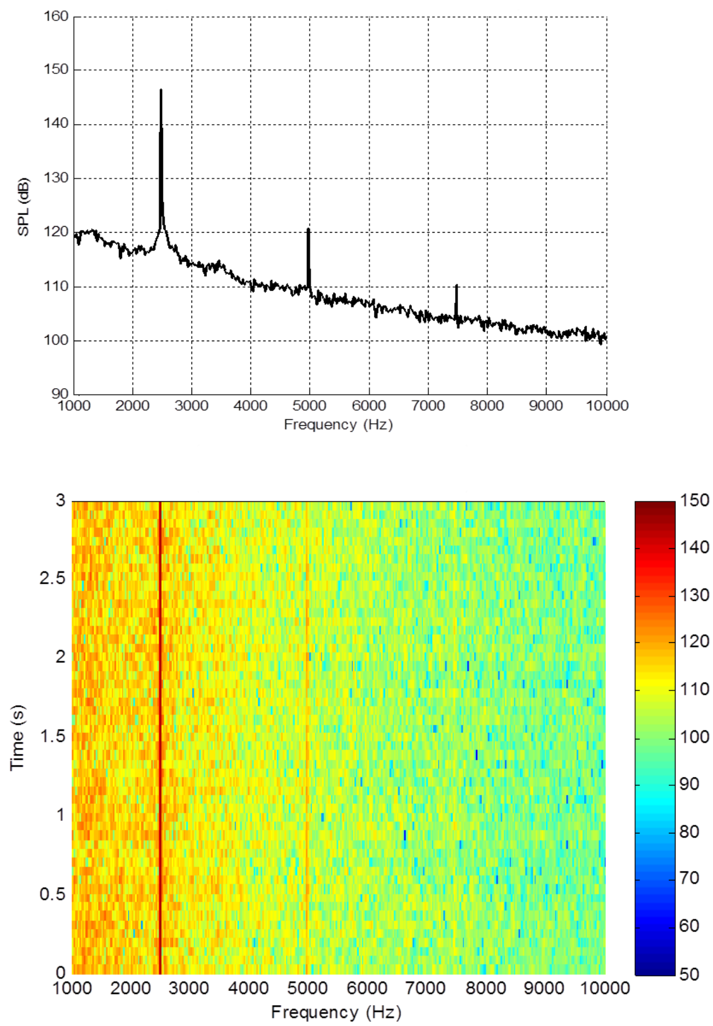


Figure 15: Baseline SPL and spectrogram for a strongly resonating cavity

B. Quasi-2-D Forcing Cases

As previously stated, quasi-2-D forcing is all five actuators are firing in phase. Several successful, almost 5 dB increase in broadband spectrum and 140 dB tonal peak, cases were found when forcing in this configuration, with the most successful being those for which the forcing frequency was around the 2nd Rossiter mode and the 1st harmonic of the 2nd Rossiter mode.

Generally the frequencies corresponding to the two strongest Rossiter modes, 2nd and 3rd are receptive to forcing to amplify resonance. From the baseline cases the 2nd Rossiter mode is the strongest peak in this experiment it was more receptive than the 3rd mode. The broadband SPL increased as the forcing frequencies came closer to the middle of the sweep especially at higher frequencies. This indicates the flow is receptive near the natural modes, but less receptive at higher frequencies. Numerous studies have indicated that high frequency forcing, at frequencies an order of magnitude larger than the natural frequency, is highly effective at attenuation [1, 3]. Tonal amplification was not effective outside of the vicinity of the two strongest Rossiter modes and the first harmonic of the dominant mode. The general trend of both amplification graphs, as will be discussed later, across all frequencies is there are rises near the natural frequencies but is less effective at amplification at higher modes. The higher the forcing frequency the less effective it is at amplification of tones and broadband spectra.

The results for quasi-2-D forcing at 2400 Hz, the natural frequency, are shown in Figure 16. Forcing at this frequency returns the weakly resonating cavity to similar broadband SPL and tonal peaks as seen in a strongly resonating cavity. The frequency shift at the 2nd Rossiter mode from the baseline to the forcing case was an observed phenomenon. The tonal peak frequency shifts to the forcing frequency in certain receptive cases, such as 2400-2500 Hz. The broadband SPL is increased by 5.5 dB and the peak is increased by 18 dB. The wide base at the peak clearly indicates this amplification is hydrodynamic in nature and not due to EMI. If the peak were due to EMI it would be sharp be only at the forcing frequency, not over a range of frequencies. This case is effective because the acoustic wave caused by the impact of the flow on the aft wall and the LAFPAs are seeding the initial shear layer in phase. The two secondary peaks are harmonics frequencies of the flow or actuators. The peak at 4800 Hz appears to be hydrodynamic for the same reasons for the 2400 Hz peak. Other notable effects of forcing are the strengthening of certain peaks while others are completely attenuated. The peaks at 3500 Hz, 6000 Hz, and 7500 Hz are gone during the forcing case. The spectrogram indicates the tonal peak and broadband are consistently amplified throughout the duration of the test Figure 17.

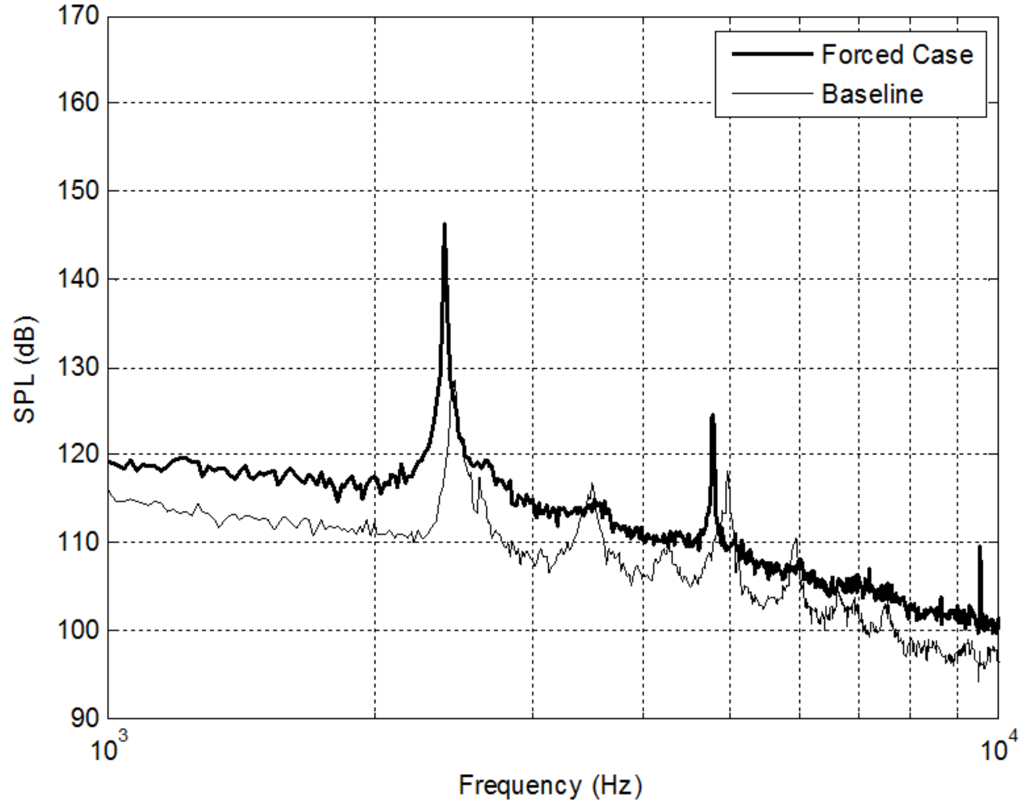


Figure 16: Baseline and 2400 Hz forcing frequency SPL comparison

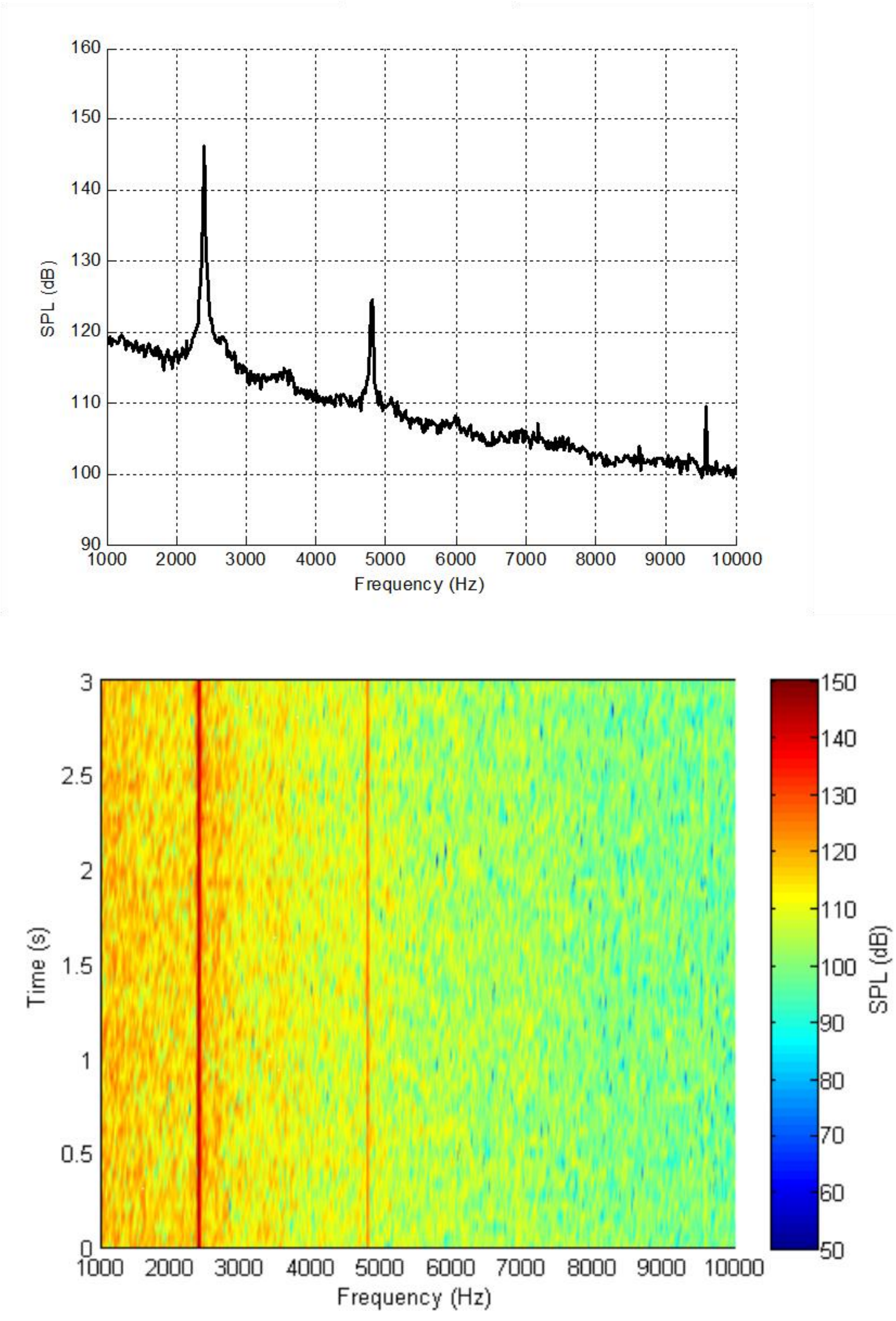


Figure 17: SPL and spectrogram for quasi-2-D at 2400 Hz

Figure 18 are the result obtained when forcing at a frequency of 3500 Hz, the 3rd Rossiter mode. This forcing was also effective. Similar to what was observed in Yugulis, forcing at 3350 Hz caused the peak near 2400 Hz to lessen in strength while the 3rd mode amplitude was increased by 15-18 dB. The 2nd Rossiter mode amplitude decreased by 8 dB indicating the 3rd mode uses most of the mean flow energy in the shear layer. Both strongly and weakly resonating cavities were receptive to tonal amplification at this frequency this further confirms that the 3rd Rossiter mode is one of the two dominant modes in this cavity flow, along with the 2nd mode. The broadband pressure was amplified by 3-4 dB and other extraneous peaks were attenuated. The broadband does not increase as much as forcing at 2400 Hz because this frequency is not the naturally dominant frequency of the cavity. The peak at 7000 Hz is EMI or a harmonic. It is impossible to distinguish the two. The spectrogram indicates the amplification occurs for the duration of the test.

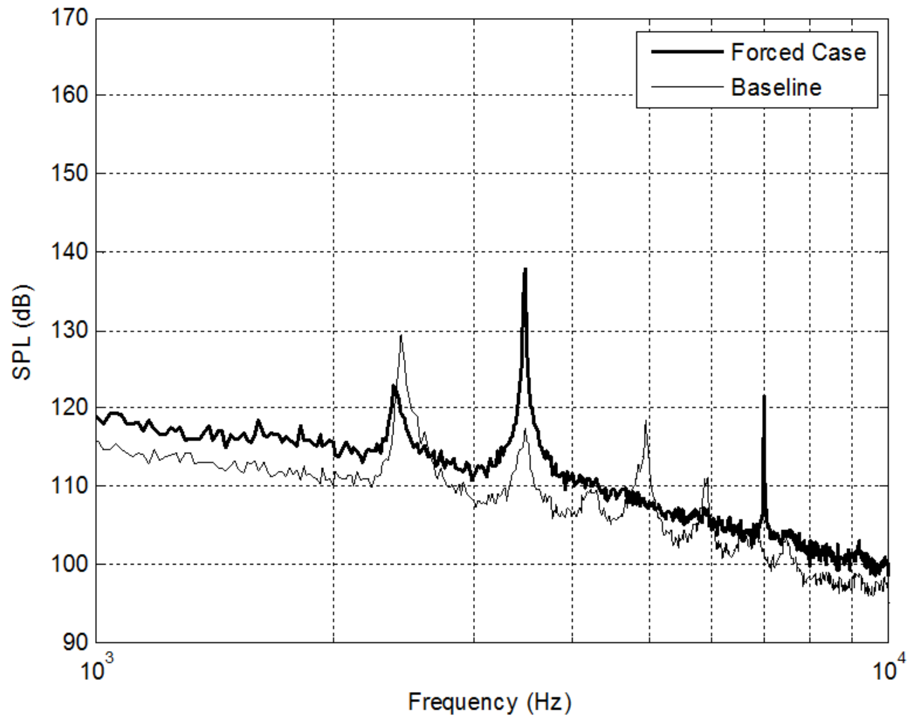


Figure 18: Baseline and forcing frequency 3500 Hz SPL

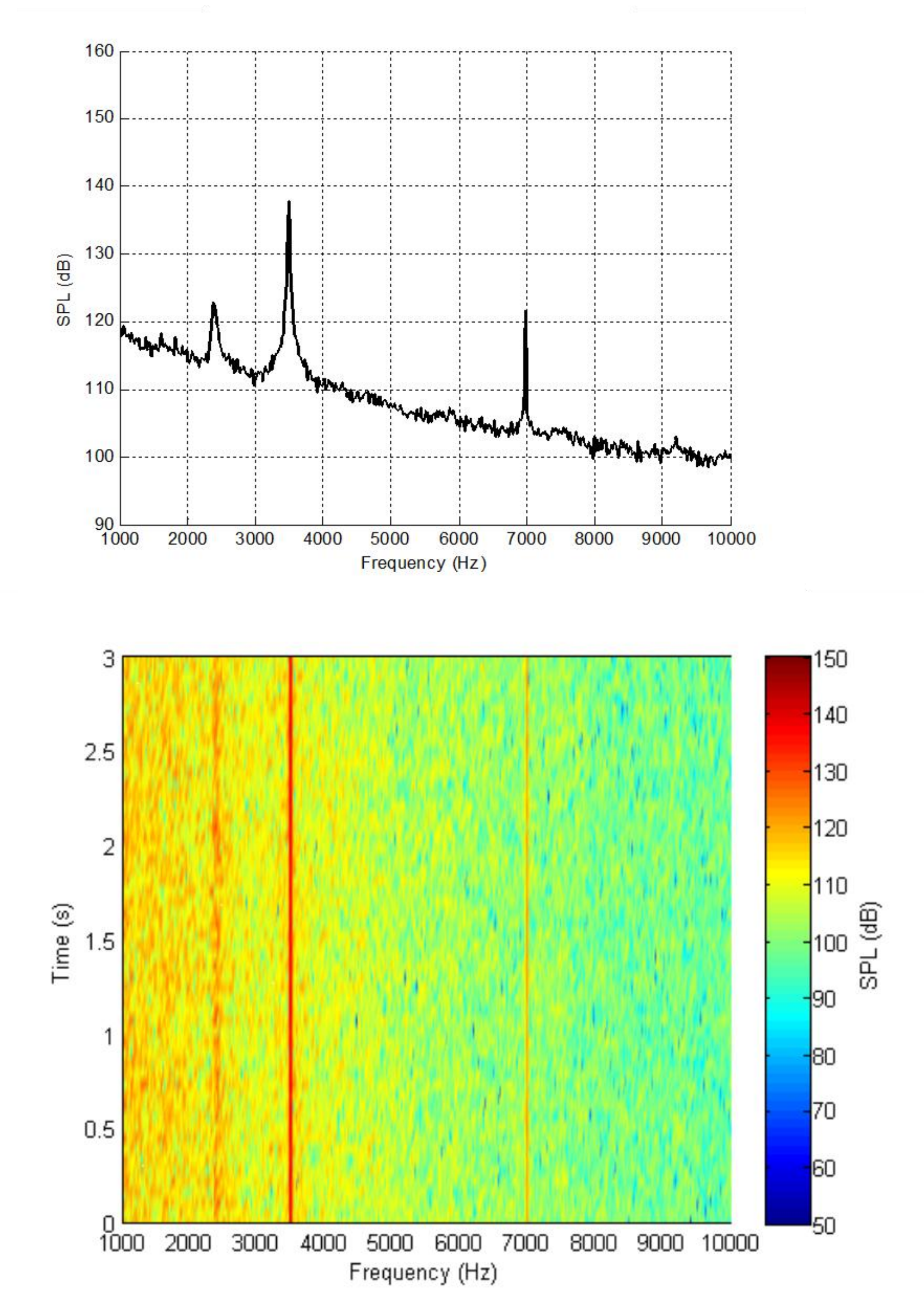


Figure 19: SPL and spectrogram for quasi-2-D forcing at 3500 Hz

The highest tested frequency at which quasi-2-D forcing was observed to be effective for resonance amplification was the 1st harmonic of the 2nd Rossiter Mode, 4800

Hz. As seen in Figure 20, the forcing caused the tonal peak amplitude to increase by 18 dB and the broadband SPL increases by close to 5 dB. The enhancement at this frequency is similar to that observed when forcing at 2400 Hz.

At 7000 Hz, the first harmonic of the 3rd Rossiter mode, and 7200 Hz, second harmonic of the 2nd Rossiter mode, no significant amplification in the broadband spectra or tonal peaks is observed. This suggests that the first harmonic of the dominant tone contains enough energy to amplify resonance, but amplification cannot occur at the harmonics of other peaks seen in the baseline spectra or higher harmonic of the dominant frequency. There is not enough energy in the harmonics of non-dominant Rossiter modes or higher, greater than the first, harmonics of the dominant Rossiter mode. Figure 21 shows that the amplification occurs throughout the duration of the test. The sustained tonal peak at a frequency of 9600 Hz can be attributed to EMI but the tonal peak at 4800 Hz is hydrodynamic based on the frequency range of the base of the peak. If a peak spans a wide range of frequencies than it is hydrodynamic whereas if it were a sharp peak it would be EMI.

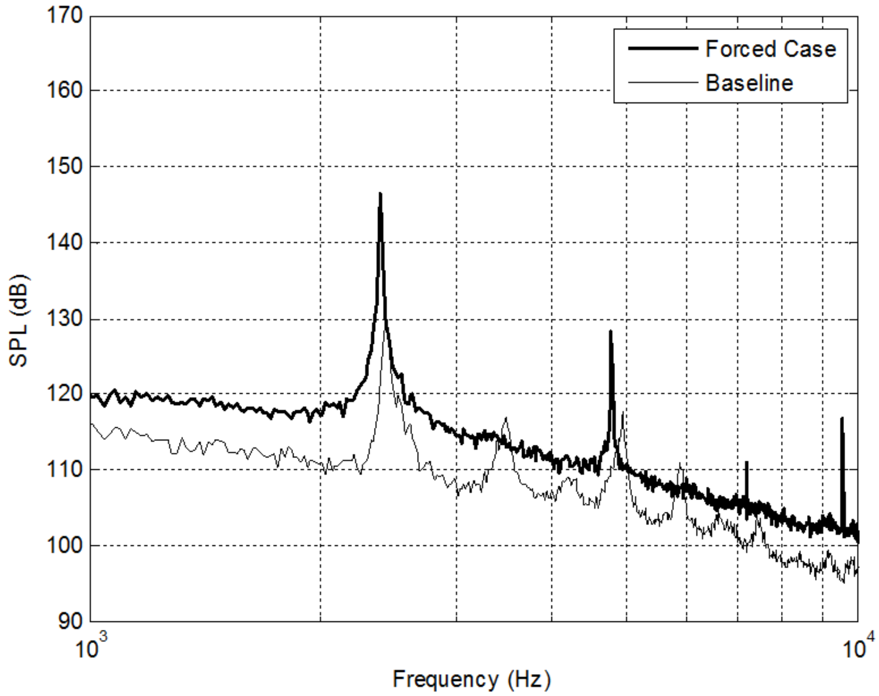


Figure 20: Baseline and forcing frequency 4800 Hz SPL comparison

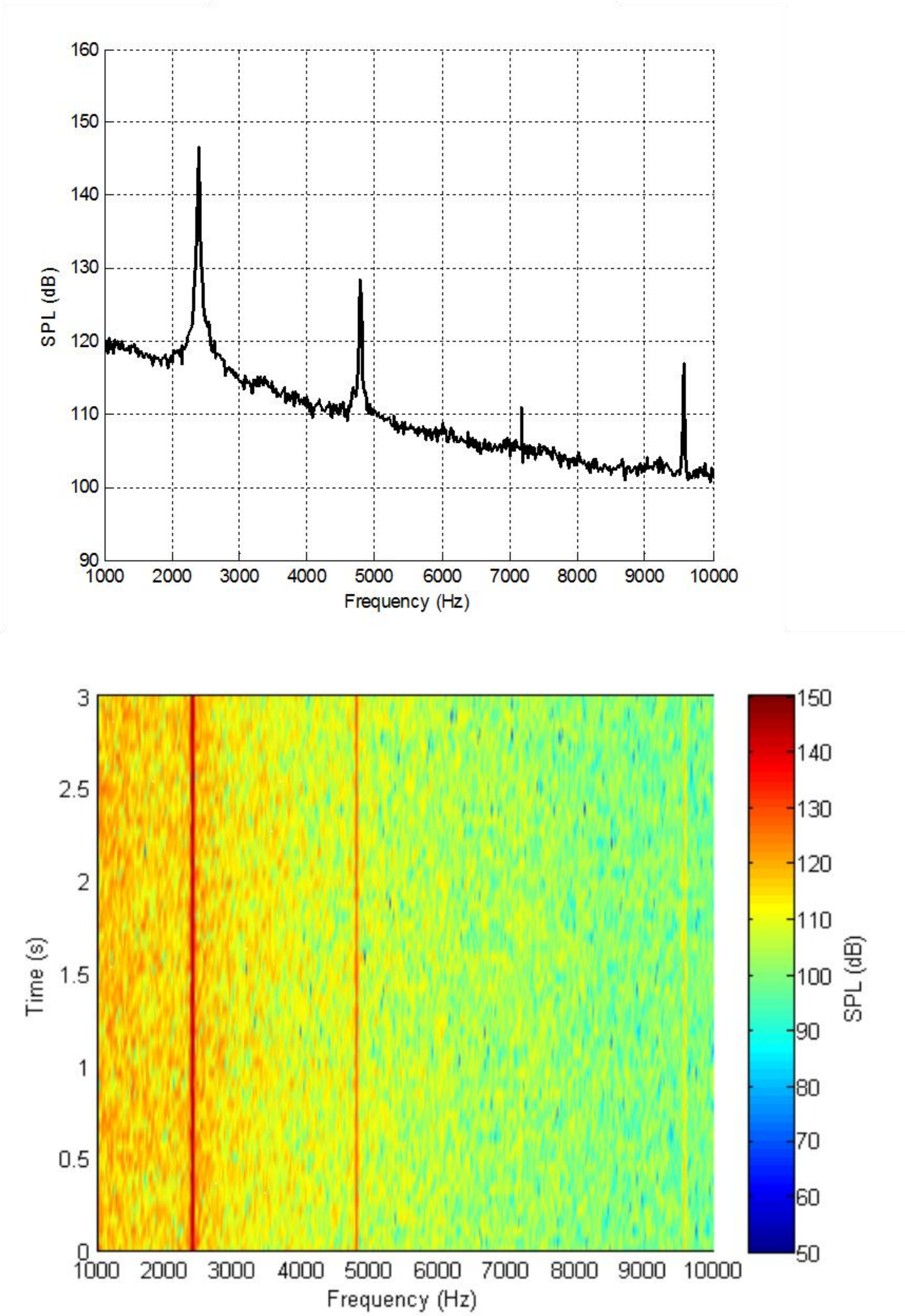


Figure 21: SPL and spectrogram for quasi-2-D forcing at 4800 Hz

The remaining effectiveness of forcing frequencies is presented in Figure 22. Graph (a) is the tonal peak amplification while graph (b) is the broadband spectrum amplification. Unlike results seen in the strongly resonating cavity, the receptivity to resonance enhancement is strongly dependent on forcing frequency. Only three regions are able to significantly increase sound pressure levels. The 2nd, 3rd, and the first harmonic of the 2nd Rossiter mode are capable in re-establishing the feedback loop. Yugulis [3] looked solely at the attenuation of the 2nd Rossiter mode, even when forcing at 3300 Hz. In this case his work actually shows an amplification of the 3rd Rossiter mode to almost 140 dB, or only a 5 dB drop from the baseline case. For this reason, this research decided to examine amplification of both the 2nd and 3rd mode. For a cavity to trap a shock wave it needs to be strongly resonating. If both of these frequencies are effective at trapping a shock wave then only the theoretical Rossiter modes would need to be calculated instead of finding the dominant mode of the cavity; which has been found to move between both of these modes when freestream Mach number increases [8]. Whichever peak was the highest was compared to the SPL of the 2nd Rossiter mode in the baseline case.

The red markers along the frequency axis are the Rossiter modes. At higher frequencies, the actual receptive frequency is seen to deviate from the theoretical natural frequency. This has been observed by other studies [3, 10]. Forcing at these natural modes increases the tonal peaks and broadband spectra more than surrounding frequencies. The actuators are observed to be effective in resonance enhancement at the Rossiter modes. Sweeps around these frequencies indicate a wide range of frequencies which are able to amplify the resonance. When forcing around 2400 Hz there is an effective bandwidth from 2300-2600 Hz which tonal peaks has increased by at least 10 dB. Compared to the 3-D forcing cases the effective range in quasi-2-D forcing is much larger. For 3-D forcing the actuators need to be operating at or near the natural frequencies.

a)

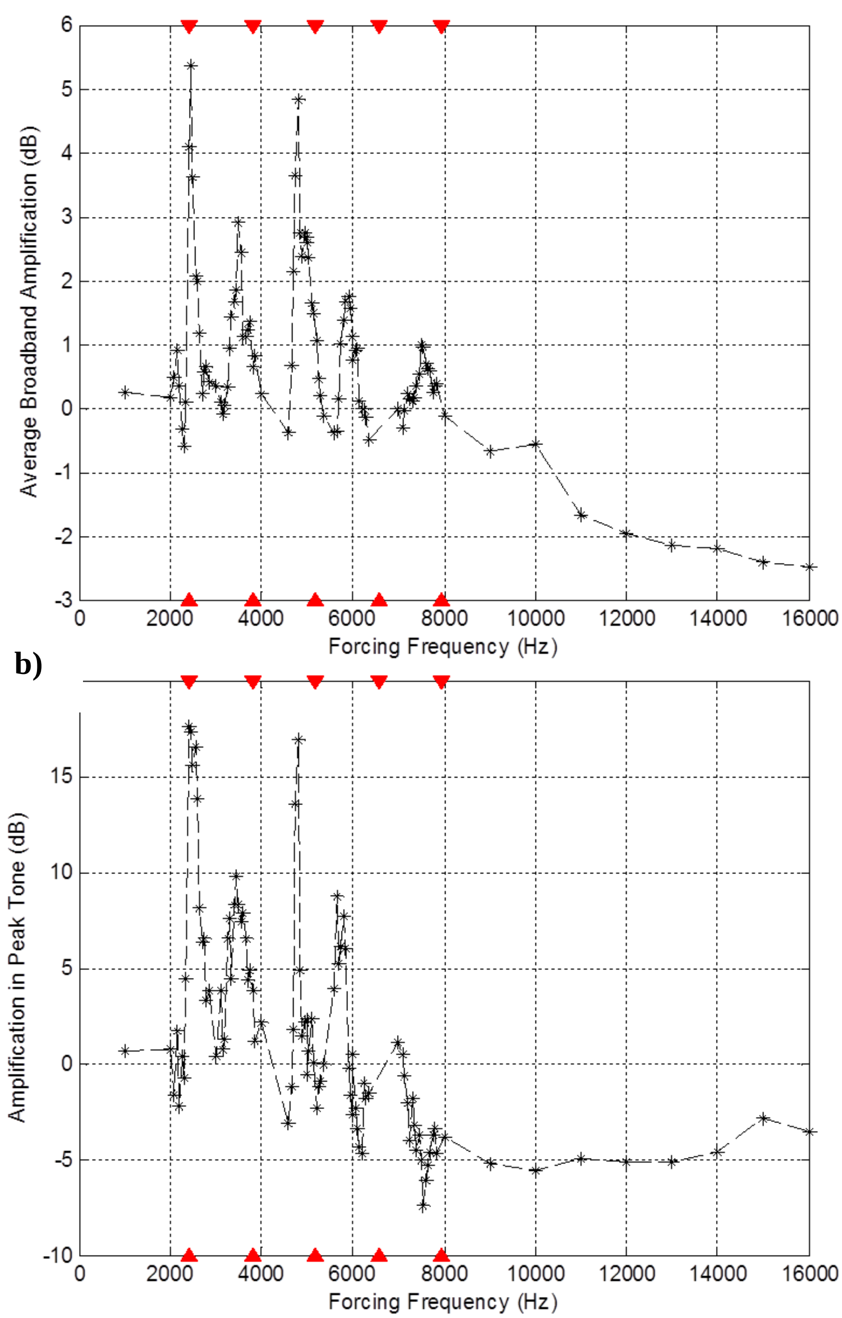


Figure 22: Tonal peak and average broadband spectrum amplification for all forcing cases

C. 3-D Forcing

The same forcing sweeps were performed with the actuators forcing three-dimensionally as well. In 3-D forcing, as was discussed earlier, the actuators operate out of phase. This is the same forcing sequence used by Yugulis [3]. In that work it was observed that forcing three dimensionally at high frequencies attenuated strong tonal peaks and broadband spectra. This was thought to be accomplished by introducing jitter into the flow. These results may indicate that this mode of forcing should not be effective at resonance enhancement. However, several different frequencies were capable of increasing resonance. The effective range around the natural Rossiter modes for which amplification was observed was, however, not as large as for quasi-2-D forcing. Forcing at the first sub-harmonic of the most effective frequencies discovered for 2-D forcing, 2400, 3500, 4800 Hz, yields similar results to what was observed in the quasi-2-D forcing. Most other 3-D forcing cases attenuated the SPL or did nothing to the SPL.

Forcing at the sub-harmonics of the 2nd and 3rd Rossiter modes yielded significant resonance enhancement. These were the only two forcing cases near these frequencies and it is unclear how large the bandwidth is in which the actuators are capable in resonance establishment. Looking at the frequency sweeps around the other theoretical Rossiter modes it is reasonable to assume the effective bandwidth is narrower but this assumption would need to be further corroborated by running frequency sweeps at the subharmonics of the Rossiter modes. Forcing at any other frequency reduces the amplitude of both the tonal peaks and broadband spectra.

Referring to Figure 23, it can be observed that the results of forcing at 1200 Hz are similar to those obtained by forcing at 2400 Hz in a quasi-2-D mode. To further validate this statement 1750, 2400, and 4800 Hz will be discussed. It is believed that the 3 actuators and the acoustic wave forcing in-phase is enough to enhance resonance despite two other actuators operating out-of-phase. The broadband increase of 3.5 dB was not as strong as those observed in quasi-2-D forcing cases; this may be indicating that 3-D forcing is not as effective at increasing resonance. The tonal peak was amplified by 18 dB. This is similar to the results of the quasi-2-D forcing. The width of the base of the peak near 2400 Hz indicates this SPL peak is hydrodynamic and cannot be attributed to electromagnetic interference. The spectrogram shows that the resonance enhancement occurred for the duration of the test. Jitter is still present in the broadband and is greater than what was observed in the quasi-2-D forcing because there are oscillations in the broadband, near 3500 Hz and between 6000 and 9000 Hz This signifies that the structures are more organized in the quasi-2-D forcing cases. PIV data would be required to confirm this hypothesis.

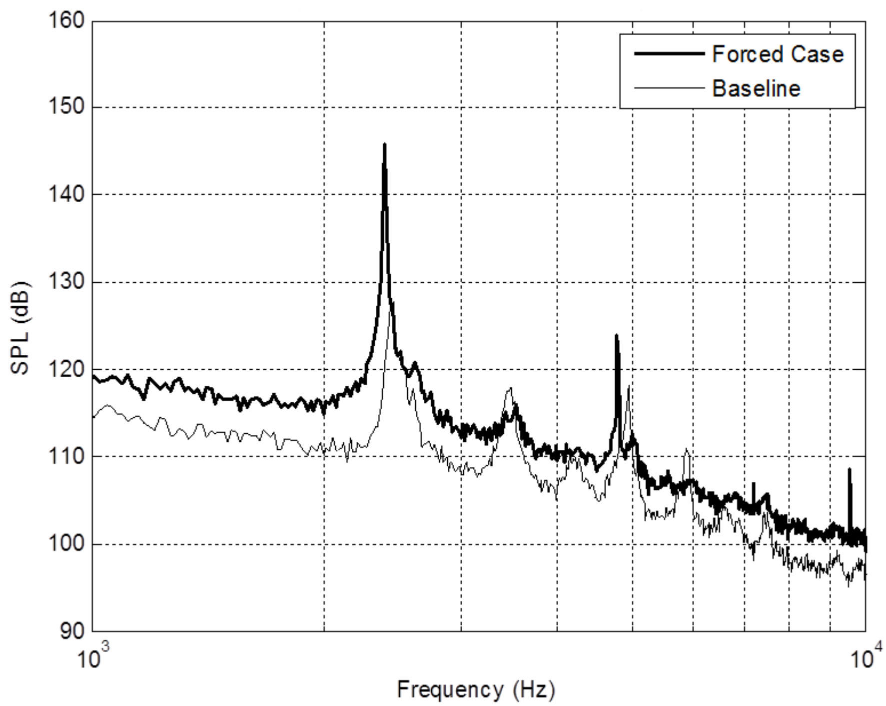


Figure 23: Baseline and 3-D forcing frequency 1200 Hz SPL comparison

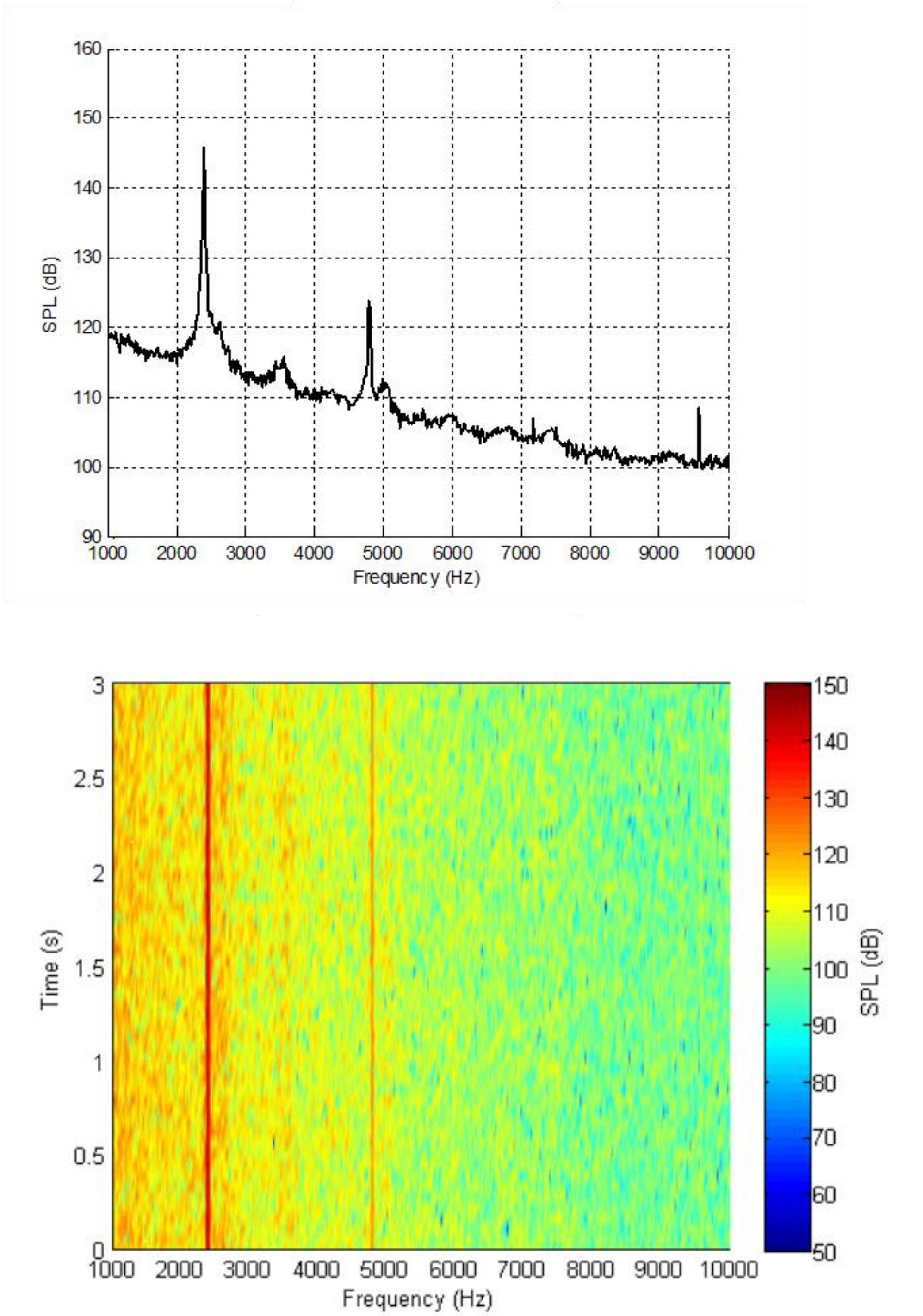


Figure 24: SPL and spectrogram for 3-D forcing at 1200 Hz

Forcing three-dimensionally at 1750 Hz should result in a similar SPL as quasi-2-D forcing at 3500 Hz. The expected result is that the peak at 3500 Hz would be amplified to a maximum amplitude of 135 dB. As seen in Figure 25 this does occur. This phenomena will be discussed more when quasi-2-D forcing and 3-D forcing are compared to one another and to what was seen by Yugulis [3]. Forcing at the sub-harmonic of the 3^{rd} Rossiter mode causes the amplitude of the peak at the 2^{nd} mode to decrease by 8 dB but the amplitude of the peak at 3500 Hz increased by 18 dB. This is a strong amplifying frequency, with a tonal amplification of 20 dB compared to the 3^{rd} Rossiter mode in the baseline. The broadband spectrum increases only slightly but this can be attributed to the 3^{rd} mode not being the naturally dominant mode. Forcing also attenuates most of the peaks, but there is still significant jitter in the broadband as compared to 1200 and 2400 Hz. The spectrogram demonstrates the consistency with which this tonal peak and broadband amplification occurred.

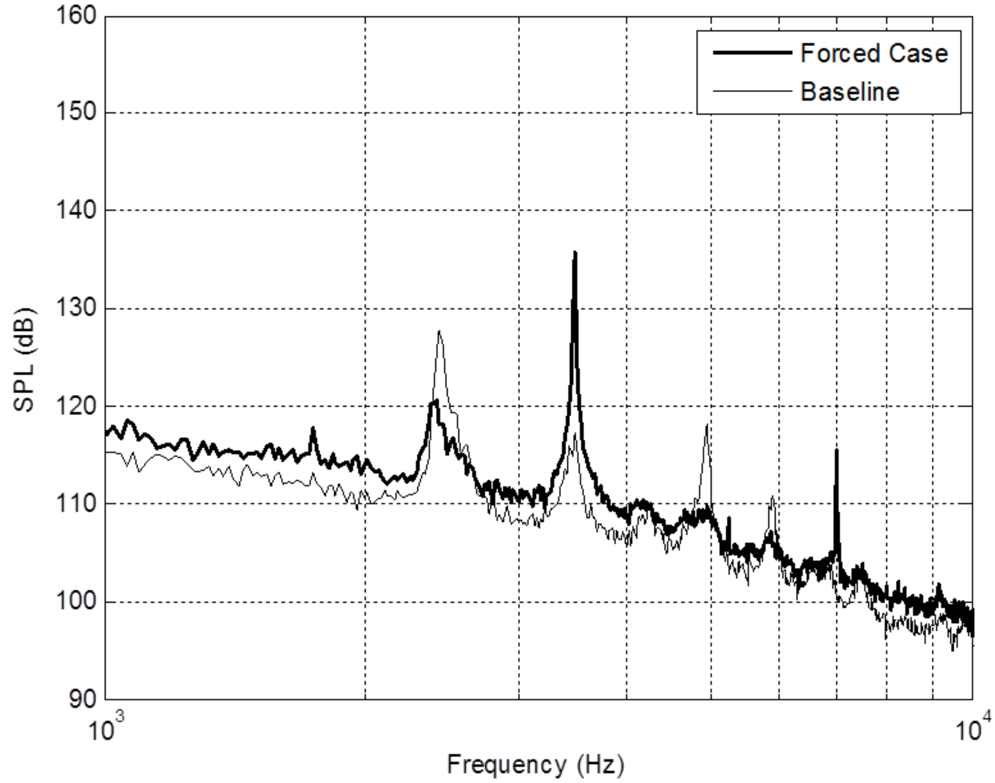
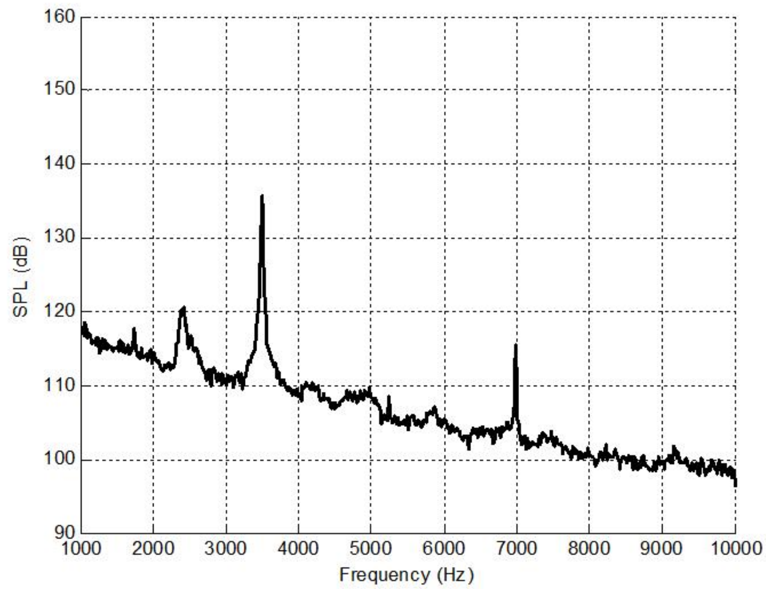


Figure 25: Baseline and 3-D forcing frequency 1750 Hz SPL comparison



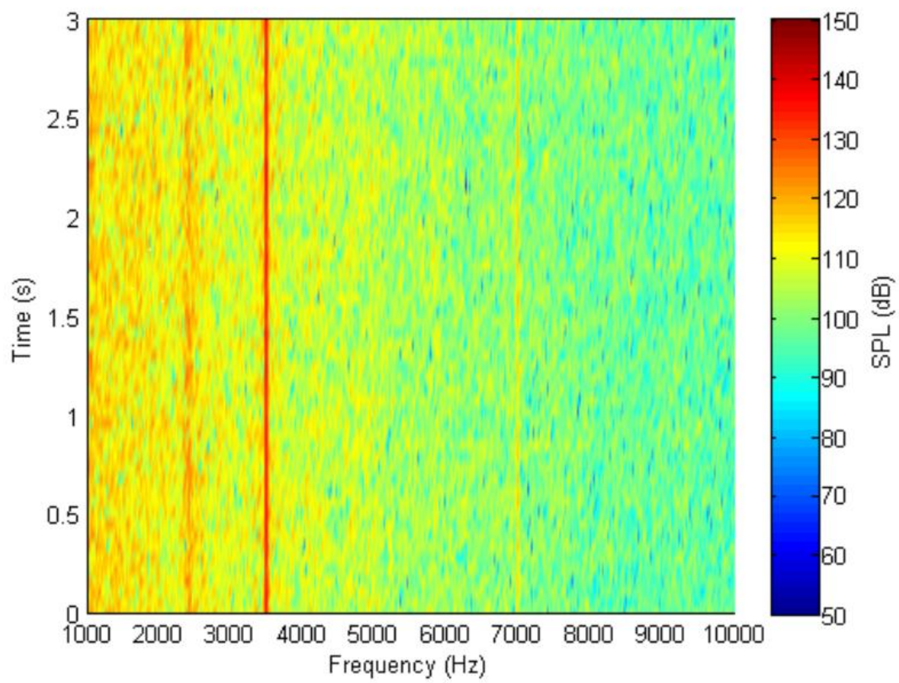


Figure 26: SPL and spectrogram for 3-D forcing at 1750 Hz

Based on the previous two forcing cases demonstrating that 3-D forcing at half the frequency of quasi-2-D forcing can have similar effects as the quasi-2-D case, it seems logical to assume that forcing 3-D at 2400 Hz would yield similar results to forcing at 4800 Hz in a quasi-2-D fashion. It is difficult to confirm this statement because for quasi-2-D forcing the cavity was receptive to both 2400 and 4800 Hz. Either way, 3-D forcing at 2400 Hz, as seen in Figure 27, yielded similar results to quasi-2-D forcing at 2400 and 4800 Hz. The spectrogram confirms that resonance is enhanced for the duration of the test. The tonal peak increases by 18 dB to a peak value of 145 dB. The broadband spectrum does not increase as much as for the quasi-2-D forcing. This is likely due to the energy input from the LAFPAs not being in phase. PIV data could help to confirm this hypothesis.

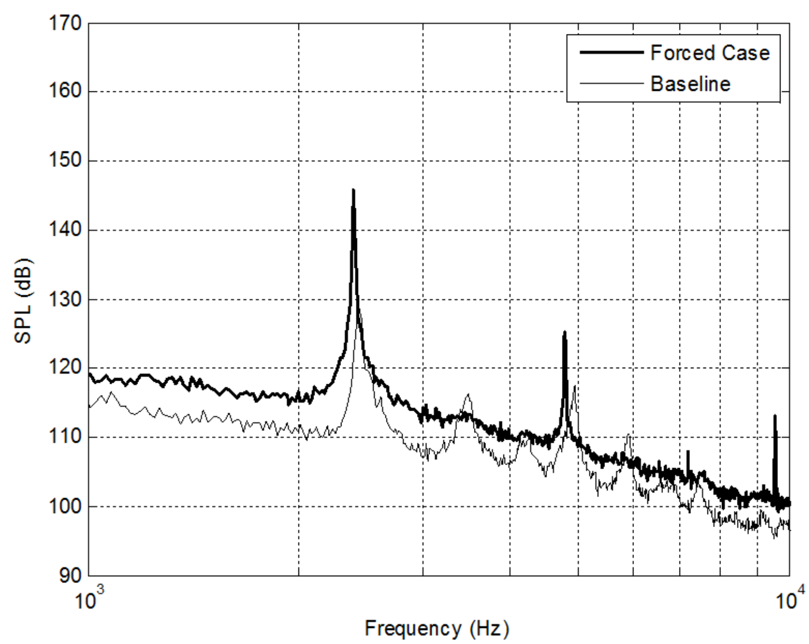


Figure 27: Baseline and forcing frequency 2400 Hz SPL comparison

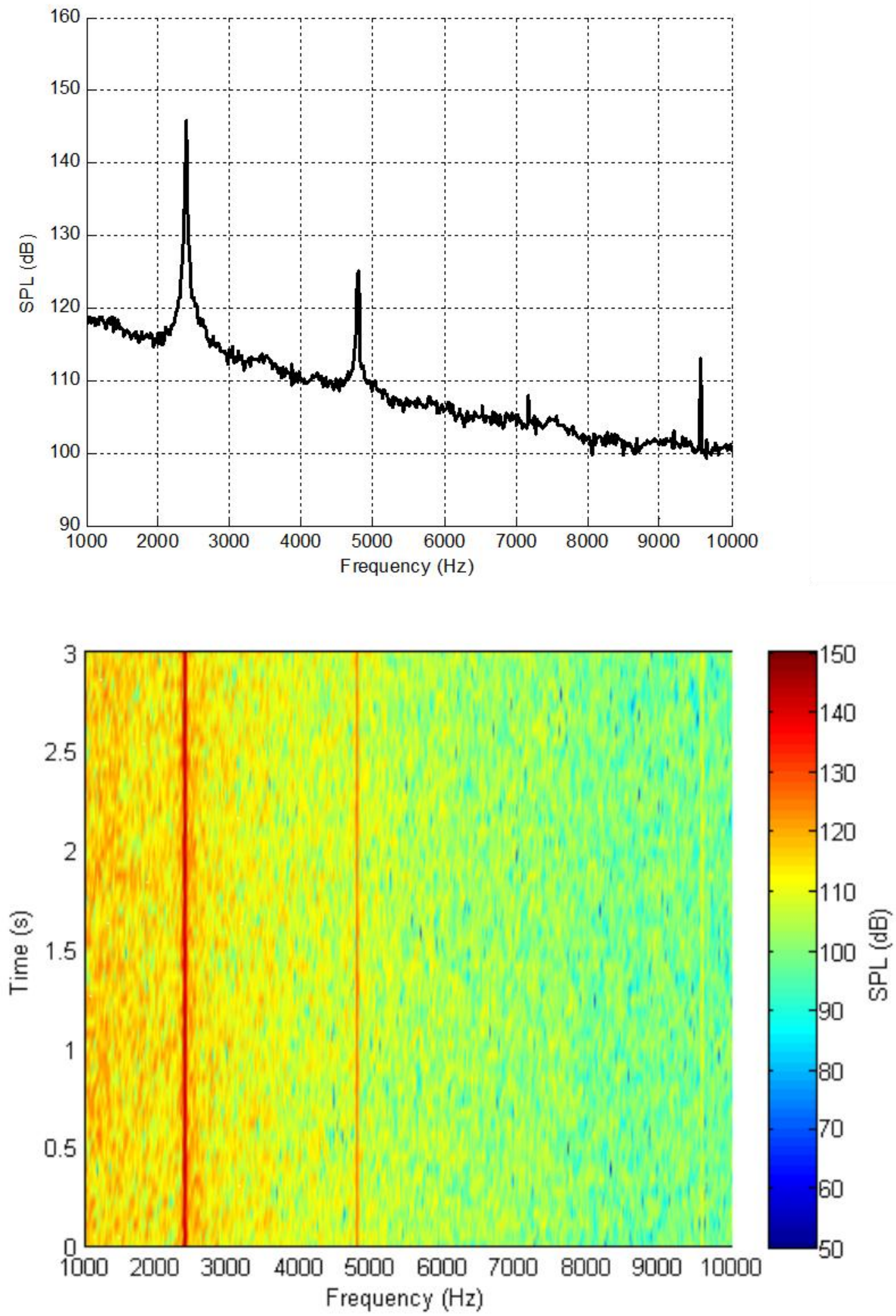


Figure 28: SPL and spectrogram for 3-D forcing at 2400 Hz

Figure 29 demonstrates that forcing at 4800 Hz does not yield similar results to forcing at the same frequency in the quasi-2-D mode. In the quasi-2-D forcing resonance is fully amplified; the tonal peak increases by 18 dB and the broadband spectrum by 5 dB. This also confirms the previous statement regarding the relationship between quasi-2-D forcing and 3-D forcing.

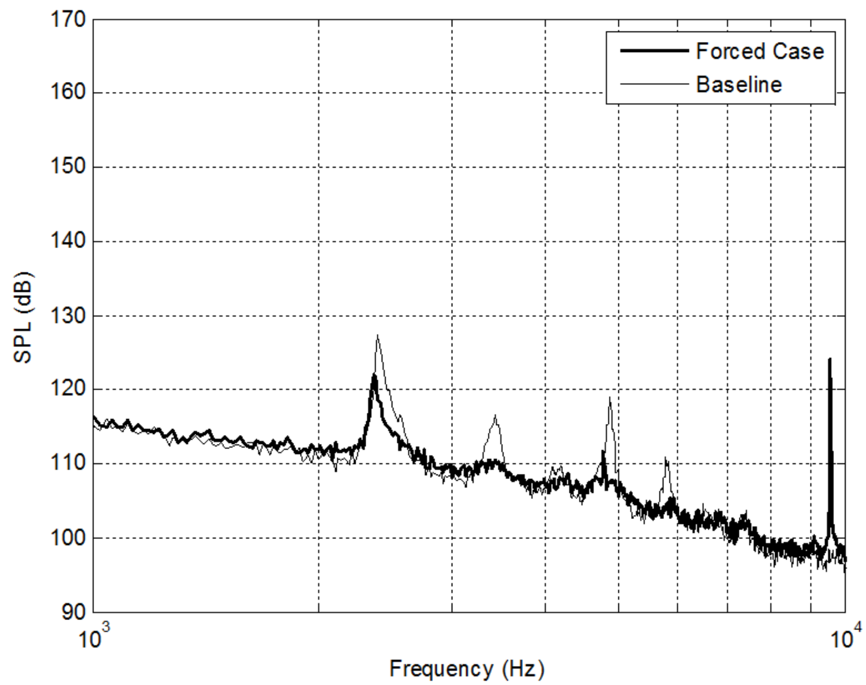


Figure 29: SPL comparison between baseline and forcing frequency 4800 Hz

Tonal peak and broadband spectrum amplification for all 3-D forcing frequencies shows there are even fewer frequencies than quasi-2-D forcing that can effectively amplify resonance, as shown in figure 30. There are only 2 cases, 1200 and 2400 Hz, which amplified the tonal peak to 145 dB, which is the maximum peak in the baseline, strongly resonating cavity (see Figure 15). As stated previously, forcing sweeps around the sub-harmonics of the 2^{nd} and 3^{rd} Rossiter modes could be conducted to corroborate this hypothesis, but this was not done due to time constraints. Instead, by looking at the general trends of the forcing sweeps, the effective range for amplifying resonance at higher modes is much less narrower than the quasi-2-D forcing. This further demonstrates the dependence on the forcing frequency of resonance amplification. Most of the 3-D forcing cases attenuate the tonal peak and have little effect on broadband spectra. This is due to the actuators introducing jitter into the flow which prevents vortices from becoming as strong as the vortices in quasi-2-D forcing [3].

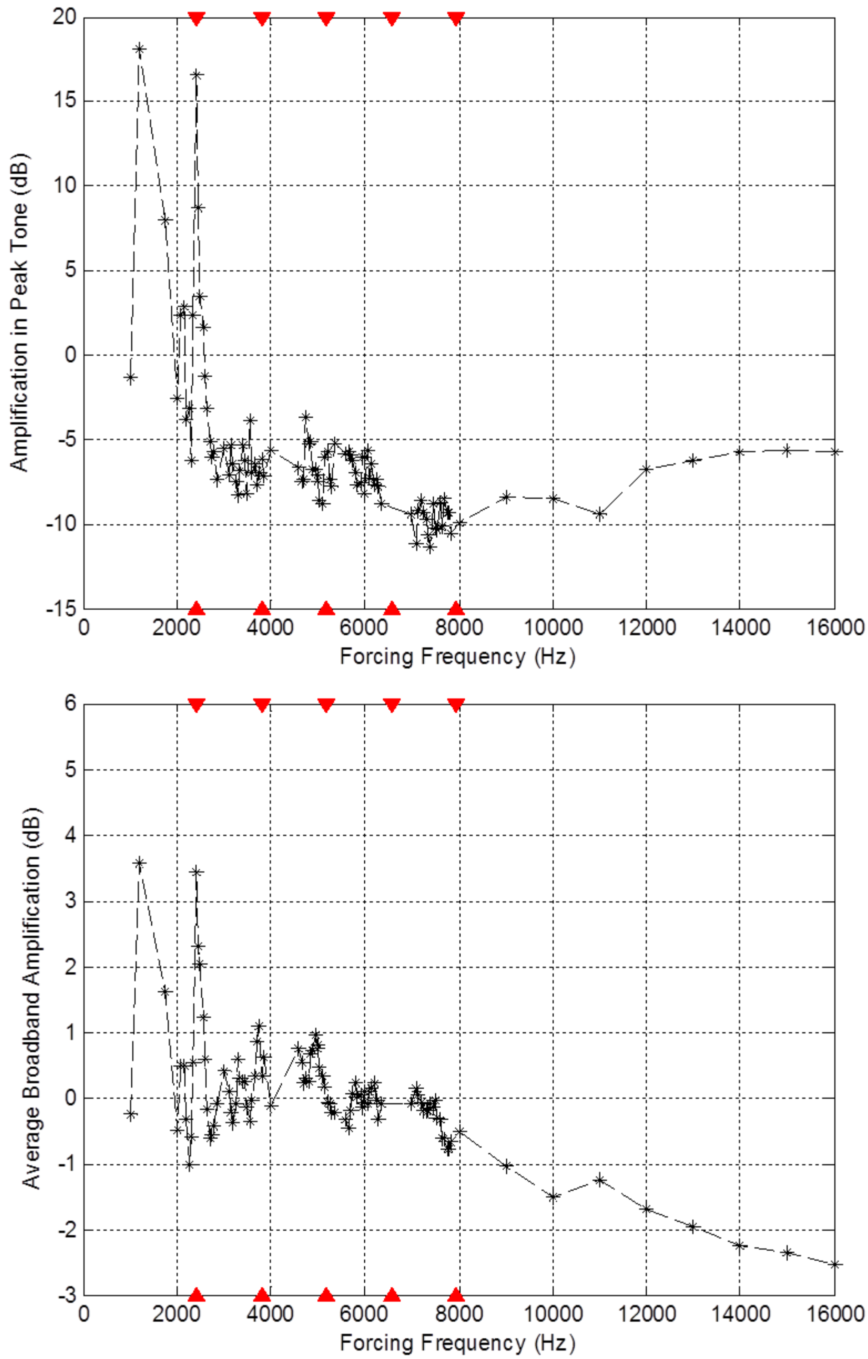


Figure 30: Tonal peak and broadband amplification for all 3-D forcing frequencies

D. Comparisons between Quasi-2-D and 3-D Forcing and a Weakly and Strongly Resonating Cavity

The maximum tonal peak for this cavity was observed to have an amplitude of about 145 dB. Obviously, this sound pressure level is different for cavities with differing freestream Mach number and cavity geometries but with results discussed earlier forcing a weakly resonating cavity can only increase to sound pressure levels to those seen in a strongly resonating cavity, as seen in Figure 31. Figure 31 (a) is a strongly resonating cavity and (b) is quasi-2-D forcing at 2400 Hz in a weakly resonating cavity forced at the dominant natural frequency.

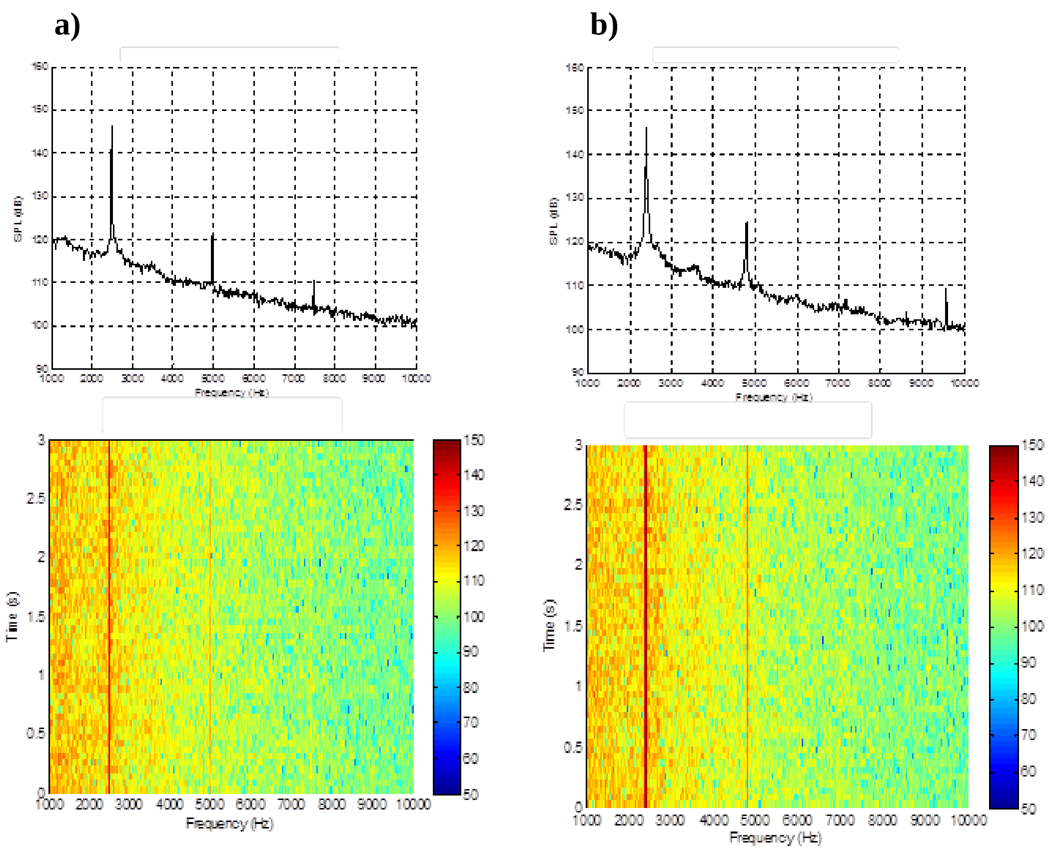


Figure 31: (a) Strongly resonating cavity baseline case and (b) weakly resonating cavity forced quasi-2-D at 2400 Hz

As stated previously the effect quasi-2-D forcing is exactly twice the effect of 3-D forcing at the most receptive frequencies. Figure 32 compares 3-D and quasi-2-D forcing for forcing near the two dominant Rossiter modes. Comparing the quasi-2-D and 3-D cases, 2400 and 1200 Hz respectively, the tonal peaks are similar in magnitude, around 145 dB, and broadband spectrums are approximately the same magnitude as well. The broadband spectrum in the 3-D forcing has more jitter though. The peak at the 3rd Rossiter mode exists in both cases, and there are other small peaks between 6000 and 8900 Hz. Figure 32 displays cases where the forcing frequency is near the third Rossiter mode. The peak around 2400 Hz is attenuated in both cases by approximately 8 dB. Jitter is seen between the 2nd Rossiter mode and its first harmonic in the 3-D forcing case, signifying the vortices are more organized in the quasi-2-D case.

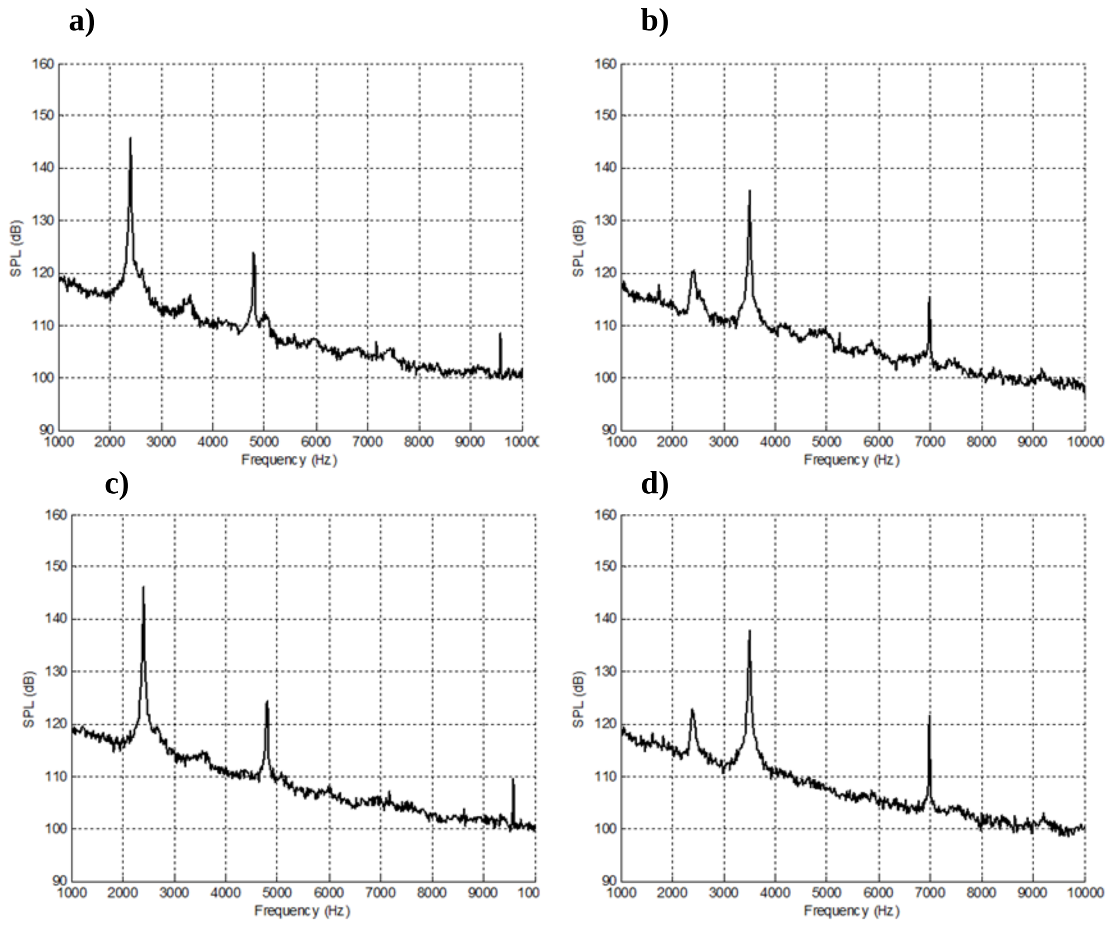


Figure 32: Comparisons between quasi-2-D and 3-D forcing at 2nd and 3rd Rossiter modes (a) 3-D forcing at 1200 Hz (b) 3-D forcing at 1750 Hz (c) quasi-2-D forcing at 2400 Hz (d) quasi-2-D forcing at 3500 Hz

As previously mentioned the 3rd Rossiter mode is one of the two dominant modes in cavity flow. The cavity in this experiment and in Yugulis [3] was dominated by the 2nd Rossiter mode but in theory forcing near the 3rd Rossiter mode should result in amplification at that frequency for both the strongly and weakly resonating configurations. In Yugulis [3] and in this experiment this was observed; the LAFPAs were able to amplify the peak at the 3rd Rossiter mode to 138 dB in both cases. This further confirms that the 3rd Rossiter mode is a dominant frequency in cavity flows.

The results suggest there is a maximum achievable peak for the natural frequency. For the 2nd Rossiter mode in this cavity, this value is 145 dB. Resonance of this amplitude was observed in both the strongly resonating cavity and the case in which the LAFPAs were forcing at that frequency in a weakly resonating cavity, (see Figure 31). Referring to Figure 33 for the 3rd Rossiter mode, this value is 138 dB; this peak was found when both the strongly and weakly resonating cavities were forced at the appropriate frequency.

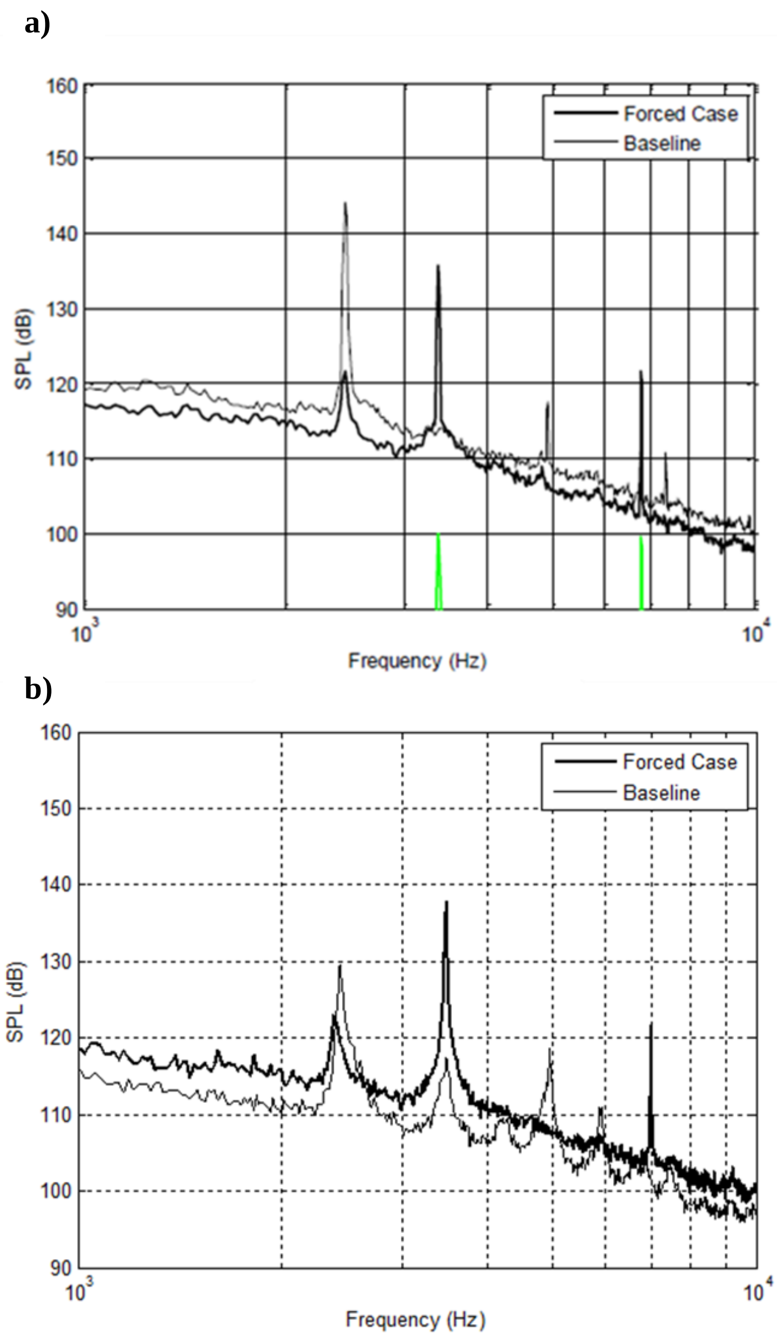


Figure 33: Forcing near the 3rd Rossiter mode for both a strongly (a) and weakly (b) resonating cavity quasi-2-D

Chapter 5: Conclusions and Recommendations

A weakly resonating cavity is forced with LAFPAs to enhance resonance. To make the cavity weakly resonating the ceiling height was adjusted 4 mm above 2 inches and baseline cases were taken to determine if this cavity is weakly resonating. The LAFPAs forced a Mach 0.6 cavity flow with a Reynolds number based on cavity depth of $2\text{x}10^5$. Five actuators evenly spaced across the span of the cavity at the leading edge forced between 1 kHz to 16 kHz. Time resolved pressure measurements acquired from Kulites on the cavity floor were used to interrogate the flow. The effectiveness of the actuators was determined by the tonal peak and broadband spectrum amplification.

Quasi-2-D forcing was found to be the most effective mode for enhancing resonance. Quasi-2-D forcing was effective over wide frequency ranges, for the quasi-2-D around 2400 Hz the effective range was 2300 to 2600 Hz, in amplifying resonance. The simultaneous energy inputs from the actuators were able to increase the broadband SPL by up to 5 dB and tonal peaks by 18 dB. The most effective cases at resonance enhancement were around the 2^{nd} Rossiter mode and its first harmonic. In general, the flow is even more sensitive to forcing than what was seen in the strongly resonating case. Forcing near Rossiter modes increased both broadband spectrum and tonal peaks but the amount of this amplification decreased significantly as forcing frequency increased. 3-D forcing effectively enhanced resonance, only at 1200 and 2400 Hz. By comparing several forcing cases between quasi-2-D and 3-D forcing the 3-D forcing frequency must at 2^{nd} Rossiter mode or its suharmonic to achieve similar forcing results at quasi-2-D forcing at the 2nd Rossiter mode and its first harmonic. The broadband spectra did exhibit more jitter in 3-D forcing cases than the quasi-2-D forcing. This can potentially be attributed to more organized vortices in the quasi-2-D forcing cases. This hypothesis would require further investigation, preferably using PIV data, to confirm.

A. Recommendations

The next step is to examine the ability of the cavity and actuators in arresting a unstart shock. The wind tunnel will need to be modified to begin researching the effectiveness of the actuators and cavity in arresting a shock train. To test the capabilities in trapping a shock train the flow will need to simulate that seen in a scramjet isolator section. The tunnel will be modified to increase the freestream Mach number to 2. In order to accomplish this, a new nozzle and various downstream components will need to be designed and built. The final objective of this project is to determine if the actuators can make a non-resonating cavity strongly resonate to arrest a shock but also make a cavity weakly resonate during normal operation. This research and the work by Yugulis [3] have demonstrated both that the actuators can enhance resonance in a weakly resonating cavity and can disrupt the feedback loop in a strongly resonating cavity.

This research has answered some of the questions posed by Yugulis [3] but has produced some additional questions. These questions are left for future researchers but the more important of these include, 1) What is the range of effective frequencies around the sub-harmonic of the dominant Rossiter mode in 3-D forcing? 2) Can both the 2nd and 3rd mode resonate strongly enough to trap a shock?

References

1. Cattafesta, L.N., III, Q. Song, D. Williams, C. Rowley, and F. Alvi, *Active Control of Flow-Induced Cavity Oscillations.* Progress in Aerospace Sciences, 2008. **44**(7-8): p. 479-502.

2. Donbar, J.M., Linn, J.J., Srikant, S., and Akella, M.R.,, *High-Frequency Pressure Measurements for Unstart Detection in Scramjet Isolators.* 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 2010. **6557**.

3. Yugulis, K., *High Subsonic Cavity Flow Control Using Plasma Actuators*, in *Mechanical and Aerospace Engineering*2012, The Ohio State University.

4. Rowley, C.W., T. Colonius, and A.J. Basu, *On self-sustained oscillations in two-dimensional compressible flow over rectangular cavities.* Journal of Fluid Mechanics, 2002. **455**: p. 315-346.

5. Lawson, S.J., Barakos,G.N., *Review of Numerical Simulations for High-Speed Turbulent Cavity Flow.* Progress in Aerospace Sciences, 2011. **47**: p. 186-216.

6. Rossiter, J.E., *Wind-Tunnel Experiments on the Flow Over Rectangular Cavities at Subsonic and Transonic Speeds.* 1964.

7. Heller, H.H.a.B., D.B., *Aerodynamically Induced Pressure Oscillations in Cavities - Physical Mechanisms and Suprression Concepts.* Air Force Flights Dynamics Laboratory, 1975. **AFFDL-TR-74-133**.

8. Malone, J., M. Debiasi, J. Little, and M. Samimy, *Analysis of the Spectral Relationships of Cavity Tones in Subsonic Resonant Cavity Flows.* Physics of Fluids, 2009. **21**(055103): p. 9.

9. Hirahara H., K.M., Khan M., Hourigan K., *Experimental Investigation of fluid dynamic instability in a transonic cavity flow.* Experimental Thermal and Fluid Science, 2006(31): p. 333-347.

10. Murray, N., E. Sallstrom, and L. Ukeiley, *Properties of subsonic open cavity flow fields.* Physics of Fluids, 2009. **21**(095103): p. 16.

11. Ashcroft, G. and X. Zhang, *Vortical structures over rectangular cavities at low speed.* Physics of Fluids, 2005. **17**(1): p. 015104: 1-8.

12. Williams, D.R., Fabris D., *Experiments on Controlling Multiple Acoustic Modes in Cavities*, in *AIAA/CEAS Aeroacoustics Comference*2000, AIAA. p. 13.

13. Debiasi, M. and M. Samimy, *Logic-Based Active Control of Subsonic Cavity Flow Resonance.* AIAA Journal, 2004. **42**(9): p. 1901-1909.

14. NASA Langley Research Laboratory, *Scramjet Engine Schematic.*

15. Webb, N., C. Clifford, and M. Samimy, *Control of Oblique Shock Wave-Boundary Layer Interactions Using Plasma Actuators*, in *6th AIAA Flow Control Conference*2012: New Orleans, LA. p. 1-18.

16. Valdivia, A., K. Yuceil, J. Wagner, N. Clemens, and D. Dolling, *Active Control of Supersonic Inlet Unstart using Vortex Generator Jets*, in *AIAA 39th Fluid Dynamics Conference*2009. p. 14.

17. Gharib, M. and A. Roshko, *The effect of flow oscillations on cavity drag.* Journal of Fluid Mechanics, 1987. **177**: p. 501-530.

18. Samimy, M., M. Kearney-Fischer, J.-H. Kim, and A. Sinha, *High speed and high Reynolds number jet control using arc filament plasma actuators for noise mitigation and for flow and noise diagnostics*, in *49th AIAA Aerospace Sciences Meeting*2011.

19. Samimy, M., M. Kearney-Fischer, J.-H. Kim, and A. Sinha, *High-Speed and High-Reynolds-Number Jet Control Using Localized Arc Filament Plasma Actuators.* Journal of Propulsion and Power, 2012. **28**(2).

20. Samimy, M., J.-H. Kim, J. Kastner, I. Adamovich, and Y. Utkin, *Active Control of High-Speed and High-Reynolds-Number Jets Using Plasma Actuators.* Journal of Fluid Mechanics, 2007. **578**(1): p. 305-330.